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Seismic Characteristics of Rockbursts for Use in Discrimination

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This research program is aimed at characterizing the seismic behavior of rockbursts and other stress-release events associated with mining for use in their discrimination. The frequent occurrence of rockbursts in mining areas throughout the world could present problems for routine discrimination at low thresholds. In addition, the possibility of controlling rockbursts in some mining areas may provide the opportunity to conceal a small or decoupled nuclear explosion test.

Review of published reports on rockbursts worldwide indicates they are frequent, occur in most mining areas, may show mechanism complexity, and may be controlled to some degree by mining practice. Although the magnitudes of most mine-induced events are small, in some regions they have exceeded 5 M_L. Seismic databases have been assembled focusing on two prominent regions of rockbursts: South Africa and Central Europe. For the former region the database includes 69 events and for the latter 44 events. A variety of time-domain and spectral

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measurements have been applied to regional as well as teleseismic signals. Some characteristics of the signals for rockbursts (e.g. Lg/P ratios) are generally similar to those for earthquakes. However, there also seems to be evidence of variations in complexity between rockbursts, which needs further study.

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I. Introduction

1.1 Research Objectives for Discrimination of Rockbursts

A key element in the identification of underground nuclear explosions has long been provided by seismic monitoring. Global networks of seismic stations, such as the AEDS network operated by the U. S. Air Force, have enabled the detection, location, and discrimination of significant underground nuclear explosion tests and earthquakes in areas of the world where such identification has been critical to treaty monitoring. Using teleseismic signals measured by such global networks, discrimination now can be provided for most events down to a fairly low magnitude threshold. However, it is recognized that there could be certain categories of seismic events or certain geographic source regions where this monitoring capability may be limited. In particular, the normal set of teleseismic discriminants may be less effective for some types of seismic events; or the seismic network used for monitoring may not record signal levels adequate for identification from sources in some areas.

The research effort described here has been directed at a type of event (viz rockbursts) for which the standard teleseismic discriminants may not be particularly effective. Furthermore, the frequent occurrence of this kind of event in hard-rock mining areas throughout the world suggests that alternative methods of signal measurement and event discrimination would be useful to facilitate their identification. This is particularly the case as additional geographic regions and lower magnitude events receive increased attention because of concerns over nuclear weapons proliferation and interest in more comprehensive weapons testing limitations. The objective of this research program, then, has been to determine the scope of the problem posed by rockbursts for seismic discrimination monitoring and to find distinctive characteristics in the seismic signals from such events which will aid in their identification. The preliminary indication, considering their frequency of occurrence, widespread nature and occasionally large magnitude, is that rockbursts represent a problem potentially greater than commercial blasting for nuclear test monitoring at low thresholds and also as a possible evasion scenario. As this research program continues, we will evaluate the feasibility that such stress-release events could be deliberately triggered to conceal clandestine underground nuclear explosion testing.

1.2 Factors Affecting Seismic Discrimination of Rockbursts

Four types of seismic sources pertinent to the problem of event discrimination are: (1) underground nuclear explosions, (2) natural earthquakes, (3) chemical blasts used in mining or construction, and (4) rockbursts related to induced stress release in mines. Of these the greatest attention over the years has been directed at discriminating underground nuclear explosions from earthquakes. However interest in lowering the discrimination threshold has indicated in recent years that greater consideration should be given to the frequent mine and construction blasts which occur routinely in many parts of the world and which could severely tax nuclear explosion discrimination methodology. Of the four types of seismic sources mentioned, by far the least attention has been given to rockbursts. Rockbursts occur in hard-rock mining areas throughout the world at depths comparable to underground nuclear explosion test emplacements. Identification of clandestine nuclear explosion tests in such an environment, therefore, could present a potential problem for seismic discrimination.

For purposes of this study, we will use the term "rockburst" in a broad sense to include all types of stress-release phenomena induced by mining and resulting in emission of seismic signals from the source vicinity. Even a cursory review of literature related to mineral exploration reveals that such events are prevalent in most underground mining and sometimes even occur with surface mining in areas of high tectonic stress. The cause of induced seismic activity in mines is understood from first principles in rock mechanics. During mining, potential energy is added to the mine surroundings equal to the product of the weight of the excavated rock and the depth of the excavation. However, only half of this energy can be stored as strain energy in the rock; the rest must be released by volume closure. Furthermore, introduction of the mine opening in prestressed rock causes readjustment of the surrounding stress field which can trigger release events in zones where the prestress was already near a critical level. Thus, the occurrence of rockbursts in mines is dependent on the volume and rate of material removed but also is intimately related to the regional tectonic stress and inhomogeneities in the nearby rock.

Because of their close connection to the ambient tectonic stress, rockbursts in many regions tend to have focal mechanisms which are earthquake-like. To the extent that rockbursts represent release of tectonic stress on zones of weakness in the rock surrounding the mine, there should be little distinction between the seismic field generated by a rockburst event and that of an earthquake in the same region. However, rockburst mechanisms may occasionally be more complex when they include non-earthquake components such as rock fall or pillar failure. Such differences in mechanism should be manifest in the radiated seismic signals. It is to be expected, then, that seismic signals generated by mining-induced events will exhibit variability depending on the proportion of events of any particular mechanism. This in turn will depend on local rock and tectonic conditions in the mine but may also be controlled in large measure by mining practice. The determination of discriminant measures for use in identifying rockbursts must take into account the predominant mechanism of the events within a particular mining region but also the range of variability in mechanism and the corresponding effects on seismic signals at magnitude levels above the threshold of interest.

Unlike natural earthquakes, which may have focal depths distributed throughout the earth's crust and in some regions even deeper, seismic events induced by mining occur at depths at or only slightly above or below the depth of material extraction. Thus, rockbursts are confined to the shallow crust since the deepest mines (viz in South Africa) barely exceed three kilometers in depth. Although the shallow focal depths may help distinguish rockbursts from many natural earthquakes, they place these induced events in the same depth range as underground nuclear tests. As a result, discriminant measures which rely on depth differences to distinguish natural earthquakes from explosions (e.g. depth phases or lack of R_g excitation) should be relatively ineffective in discriminating rockbursts from explosions. In applying a seismic discrimination scheme to a mining region with known rockbursts, relatively low weights should be applied to such depth-dependent discriminant measures.

Although the majority of seismic events induced by mining are likely to be small, their magnitudes occasionally (and in some areas regularly) have exceeded 5.0 m_b. Within a given mining area, the maximum magnitudes of the induced events show a tendency to increase with time as the depth and total volume of excavation increase. In comparison, explosions at the earth's surface connected with quarrying, strip mining or construction seldom have magnitudes greater than 3-4 m_b; and explosions used in the development of underground mines are usually in the range 1-3 m_b. Therefore, considering their magnitudes and frequency of occurrence in mining areas, rockbursts are likely to present a more significant discrimination problem than commercial blasts in many parts of the world. Furthermore, procedures which have been developed to automate and facilitate regional discrimination of commercial blasting (e.g. through detection of ripple firing) would not be expected to help with these induced events.

A final factor important to the seismic discrimination of rockburst events is the ability to control their occurrence. For many years now mining engineers have been operating seismic networks and systems of strain gauges in active mines to assist with the prediction of rockburst occurrence and with amelioration of potential damage from such events. In addition theoretical modeling techniques now enable fairly accurate representation of stress alteration in the surrounding rock due to mining excavation if the material properties of the medium are known. As a result, procedures exist in some mines to identify the imminent occurrence of stress-release events, to characterize their potential hazard and to trigger their occurrence so as to minimize damage. While such developments are welcome news to the mining industry, they could be a cause for concern for monitoring potential underground testing of low-yield nuclear explosions. It seems likely that a large stress-release event induced by mining might easily conceal a small underground nuclear explosion occurring nearby. The problem which needs to be considered is whether or not the timing and location of such large rockburst events can be controlled to coincide with a nearby clandestine nuclear explosion detonation.

1.3 Seismic Observations from Rockburst Events

The major objectives of this research program are to improve capability to characterize the seismic source from rockburst events and thereby enhance their discrimination and to perform discrimination analyses on seismic waveform data from rockburst events in a variety of source environments around the world to empirically define behavior in the radiated seismic signals useful for event identification. Most of our work to date on the former objective has focussed on literature review to determine the range of mechanisms represented by rockburst sources and assessment of how such mechanisms would affect seismic signals at teleseismic and regional distances which may be used for discrimination. For the data analysis element, we have focused on observed signals primarily from two source areas (viz South Africa and Central Europe) where frequent and large rockbursts are known to occur and where the high quality data from regional and teleseismic stations enable more complete time-domain and spectral comparisons of the recorded waveforms.

The current database was assembled from IRIS, GDSN/SRO and GSETT-2 data archives and includes waveforms for just over 100 events from the two areas. Because of their small size, the best seismic signals from most of the events are those obtained at regional stations. However, we have also collected all available far-regional and teleseismic data for the events wherever possible. To enable discrimination studies we have included in the database events believed to be natural earthquakes and mining explosions along with the presumed rockbursts from the two source areas. We have made a variety of amplitude and spectral measurements on the recorded seismic phases from the different events. Comparisons of these measurements, which have been made to date, suggest possible differences between events of different source type. However, in general the rockburst measurements tend to be earthquake-like with regards to the relative excitation of regional L_g versus P signals. Although the measurements for rockburst events from a specific source area are frequently remarkably consistent between events, there appear to be occasional differences suggestive of variations in the complexity of the rockburst mechanisms between events. Furthermore, we see some evidence in the changes in signal behavior between stations for common events that the rockburst mechanism may cause azimuthal variations.

1.4 Report Organization

The report is organized into six sections including this introduction. Section II describes the occurrence of rockburst events worldwide and provides additional information on the phenomenology and modern techniques for prediction and control. Section III details our database collection efforts to date. Time-domain and spectral analyses of the waveform data from rockbursts and other nearby event types, which may be useful for discrimination, are described in Section IV. Section V discusses rockburst mechanisms in relation to other types of seismic sources, draws inferences regarding their discrimination based on mechanism differences, and considers some possible scenarios for clandestine nuclear explosion testing in a rockburst environment. Finally, Section VI summarizes our observations to date and describes plans for our continuing investigations.

II. Worldwide Occurrence of Rockburst Events

2.1 Review of Associated Phenomena

This section reviews reports of the occurrence of rockbursts and induced seismicity in the vicinity of large excavations from several countries around the world. Rockbursts have been reported from almost anywhere there are deep mines in hard rock. Additionally, rockbursts and induced seismicity have been reported in the vicinity of shallow mines, open-pit mines, and in road tunnels on several continents. Figure 1 is a map showing locations of mining areas where rockbursts have been reported. In this review we consider where rockbursts occur and associated phenomena describing the conditions of their occurrence.

The ambient stress in the earth's crust is perturbed by mine excavations, which in turn results in localized stress concentrations in the vicinity of the mine opening. These localized stresses occasionally exceed the strength of the surrounding rock in some area producing failure or rupture and the consequent emission of seismic energy. The nature of the failure process and the associated seismic mechanism depends in a complex manner on several factors related to local tectonics, rock properties, and also mining operations. We will discuss the seismic mechanisms from such events in more detail in Section V below. We focus here on several of the principal factors controlling rockburst occurrence and descriptions of the parameters observed around the world in association with these events.

One factor affecting rockburst occurrence is mine depth. The rock overburden produces lithostatic stresses which increase with depth below the earth's surface. Stress measurements from various areas indicate that the vertical component of stress is normally adequately represented by the lithostatic pressure, but horizontal stress components are frequently significantly higher or lower than predicted by the simple lithostatic models (cf. Cook, 1976). Rockburst events associated with shallow mining illustrate the fact that in many localities ambient horizontal stresses exceed vertical stresses down to depths of about 2000 m. At greater depths, the horizontal stresses decrease to hydrostatic values. Blackwood (1979) reported that for Europe and North America the peak horizontal stresses may be expected to occur at a depth of about 750 m. This calculation appears to be consistent with historical experience with coal mines in

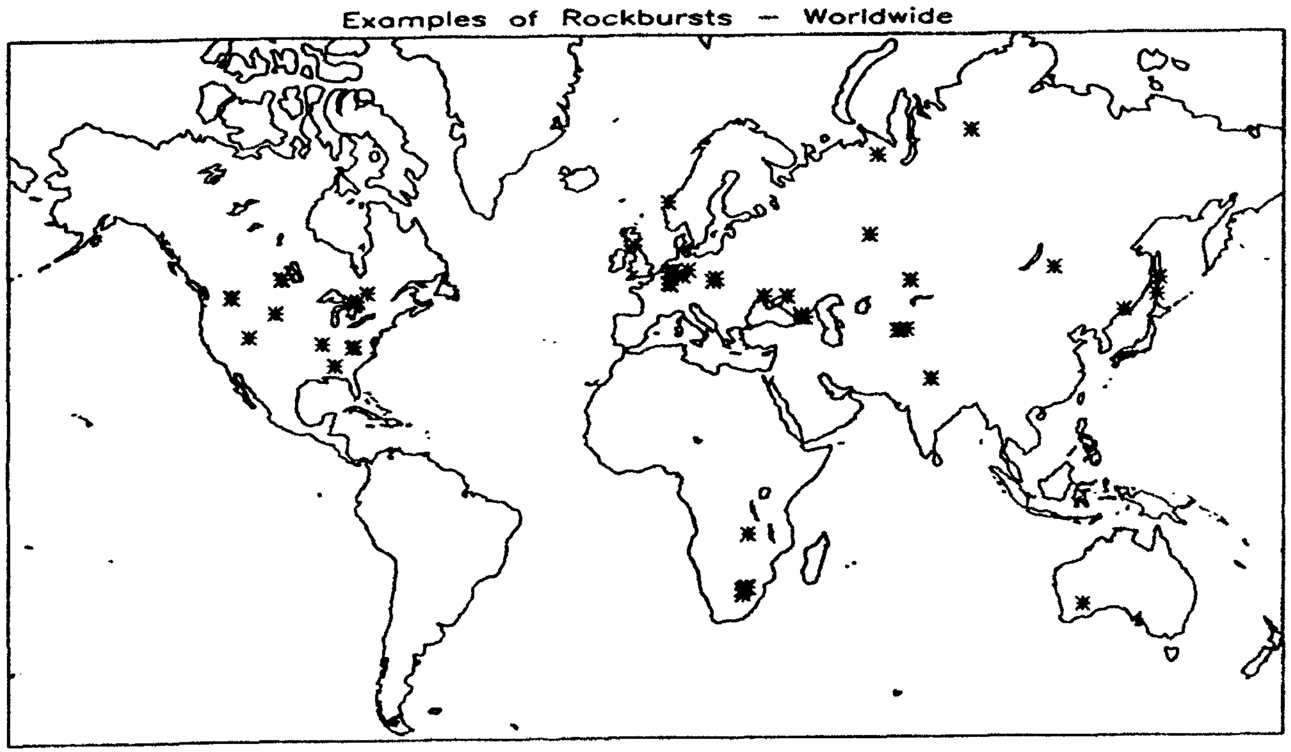

Figure 1. Locations of mining areas with reported rockbursts or tremors.

Germany where rockbursts and gas outbursts begin at depths of about 600 m, occur with increasing frequency down to about 1000 m, and then decrease in frequency down to a cut-off depth of about 1400 m. However, for coal mines in North America, the peak occurrence of rockbursts is between 200 m and 300 m; and for Australia the occurrence rate increases down to the current mining depth of 500 m. That these depths are shallower than the depth of the peak horizontal stress indicates the importance of local geologic structure and in-situ material properties on the occurrence of rockbursts.

The amount of material removed from an excavation and the rate at which it is removed also play an important role in the occurrences and sizes of rockbursts. Experience with near-surface potash mines in Canada indicates that the sizes (area of the rupture surface) associated with induced seismic events are comparable with the areas from which the material was removed. Experience in South African gold mines indicates that the rate of large rockbursts increases or decreases depending on the rate at which material is being removed from the excavation. These observations support a model for rockburst mechanisms based on the reciprocity theorem and indicate that one may be able to predict the size of an intentionally triggered rockburst in an existing mine.

2.2 Rockbursts in the Commonwealth of Independent States (CIS)

Rockbursts have occurred in both coal and mineral mines in several of the republics of the former Soviet Union according to investigations by the USGS Military Geology Branch (1992). The earliest reports of rockbursts in the CIS are from the Kizelovsk coal basin in the Ural Mountains beginning in 1947. Within the next ten years, rockburst activity began in several mines in the Donetsk basin near the Caspian Sea. As more mines began to reach depths of 200 meters or more, rockbursts and coal and gas outbursts became more common in other mining regions. Currently, there are 14 coal mining regions and 14 salt or metallic ore mining areas throughout the CIS where there is substantial rockburst activity. In general, the reported depths of rockbursts between 1966 and 1975 are 670 m or deeper. A few shallower events have also occurred in the Donbas and the Donetsk coal basins and in the iron mining region of Krivoy Rog, which is at the southern edge of the Donetsk basin. During this ten-year period, 2807 coal and gas outbursts were reported throughout the several republics

(Dubinov, 1982). Many of these rockburst-prone regions are in republics along the southern border of the CIS (e.g. Kirghizia, Tadjikistan, and Kazakhstan). The occurrence of rockbursts in these areas indicates that there could be similar events in adjacent countries such as Iran, Iraq, and Pakistan where similar tectonic stress conditions prevail. The lack of reports of such events from the latter countries may be related to limited mining development or simply failure to identify events as mining related.

2.3 Rockbursts in Poland

Reports of rockbursts in Poland are extremely interesting since they encompass both events associated with deep mining and with open-pit mining within a single geographic area. It should be noted that events associated with open-pit operations are more properly classed as induced seismicity rather than rockbursts, although there is no formal dividing line between these designations which is generally accepted. The mining regions of Poland are the site of considerable induced seismic activity as shown in Figure 2. The large number of seismic events and mine blasts in these areas should prove to be a valuable source of data for discrimination analyses.

Between 1971 and 1981 four events with magnitudes greater than 4 M_L occurred in three different mining districts in Poland. These events are listed in Table 1 below. Using a Brune seismic source model, these events were interpreted by Gibowicz (1984) as having the source parameters shown in Table 2. The inferred mechanisms determined from analysis of the first motions were reverse dip-slip for the Belchatow event, normal dip-slip for the Lubin and first Bytom events, and strike-slip with some reverse motion for the latter Bytom event. In the models for rockburst mechanisms, dip-slip motion is consistent with concentrations of stress near the edges of the excavation. In the case of the Belchatow event, the reverse mechanism would be consistent with substantial vertical unloading above a region with moderate to large horizontal stresses at depth. We will provide more detail on observed seismic source mechanisms for rockbursts and their implications for seismic identification techniques in Section V below.

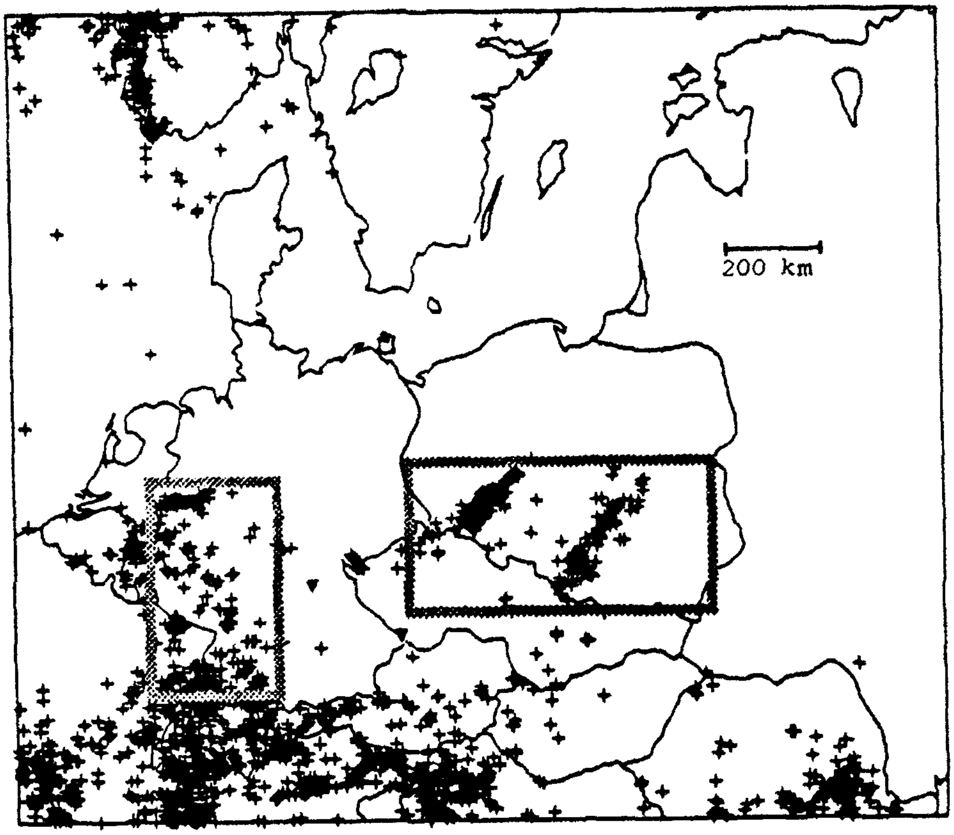

Figure 2. Locations of European mining areas in Poland (east) and Ruhr district (west) producing induced tremors. Seismicity from ISC catalog 1987-1990.

Table 1. Large Rockbursts in Poland

Date	Time	Location	Depth(km)	M_L	Region
03/24/77	07:32:26	51.5N 16.1E	1.3	4.5	Lubin
09/30/80	01:02:58	50.3N 18.9E	0.8	4.3	Bytom
11/29/80	20:42:19	51.3N 19.4E	2.0	4.6	Belchatow
07/12/81	11:59:28	50.3N 18.9E	0.7	4.1	Bytom

Table 2. Seismic Source Mechanisms for Polish Rockbursts

Date	f_o	r (m)	u (cm)	$\Delta\sigma$(bar)	σ_{app}(bar)
03/24/77	0.65	1000	3.3	9	2.5
09/30/80	1.20	430	5.5	28	3.5
11/29/80	0.63	810	7.4	21	3.0
07/12/81	0.90	580	3.0	12	1.6

2.4 Other European Rockbursts

Rockbursts also have been associated with mining activities in several other European countries. One of the largest events of this type occurred on March 13, 1989 in Germany. The event was assigned a magnitude of 5.4 m_b and was located in the Ernst Thaelmann mine near 50.7°N 9.9°E. We are currently retrieving all available digital station data from this event for discrimination analyses. Rockbursts in the Ruhr mining district of Germany (cf. Figure 2 above), the Donbas coalfield in the former Soviet Union, the Otrava-Radnavice district of Czechoslovakia, and in Great Britain all seem to be related to a common mining condition according to Whittaker (1983). Each of the areas has coal seams with layers of competent sandstone overlying the coal. The sandstones in these mining districts generally show no evidence of faulting or other pre-existing signs of geologic weakness at the mining depths near 500 to 800 m. On the other hand, coal mines in France and South Wales, where rockbursts also occur, do show considerable deformation, including folding, in the overburden rock.

While rockbursts at depths of several hundred meters are fairly common phenomena, there has also been experience with very shallow rockbursts in northern Europe associated with highway tunnel construction. Myrvang and Grimstad (1983) reported several instances of rockbursts in long tunnels being driven across the toes of fjords in Norway through Pre-cambrian gneiss formations. They attribute the rockbursts there to large horizontal stresses related to proximity of the excavation to the free surface of the mountain face.

2.5 Rockbursts in North America

Rockburst reports in the United States and Canada include coal mines in Virginia, West Virginia, Pennsylvania and Utah. Induced seismic events have also been associated with mines in Alabama and Missouri. However, some of the more complete descriptions of North American rockburst activity come from mines in Canada where there have been seismic events associated with coal mines in eastern and western Canada, with potash mines in Saskatchewan, and with metalliferous mines in Ontario.

Canadian coal mines have lengthy records of mining-induced seismicity. Records of mine tremors at the Springhill mine in Nova Scotia starting in 1916 indicate a peak in activity between 1923 and 1930 followed by a low level of activity from 1930 to 1950. The transition in activity rate corresponds to a switch in mining technique from room-and-pillar to retreating longwall. However, starting in 1950 rockburst activity at Springhill increased and finally escalated into a disasterous rockburst in 1958, which killed many miners and caused the mine to be permanently closed. Hasegawa et al. (1989) report that factors contributing to this large rockburst were (1) the large overburden pressure because of depth (viz 1200 m), which in fact exceeded the strength of the coal seam, (2) poor caving characteristics (i.e. strength) of the roof, (3) large distance between roof and floor of seam, (4) alignment of mining faces in adjacent levels of the excavation, (5) high neotectonic stress field at shallow depths in the region, and (6) high frictional resistance between the coal seam and the host rock. Thus, the size and frequency of occurrence of rockbursts in this mine appear to have been dependent on a combination of factors related to mining techniques as well as rock and tectonic conditions in the vicinity.

A more recent case of induced seismicity in Canada occurred in Saskatchewan. The induced seismicity began there in 1968 in an area of potash mining with little history of prior natural seismicity. Two interesting features of this activity are the relation to the extent and rate of mining. The event magnitudes, which range from about 2.3 to 3.1 M_L, appear to vary in size depending on the size of the mining panels (and hence the area of the mined-out region) near which they occur. The host rock for this mine is bedded salt. The physical behavior of this material is that it is plastic at the pressures and temperatures observed in the mine. Therefore, when subjected to a change in stress that occurs slowly, the salt deforms plastically. However, if the salt is subjected to a fast change in stress, it fractures. This suggests that more rapid excavation associated with mining should tend to induce more frequent and larger seismic events.

2.6 Rockbursts in Australia

Reports of rockbursts in Australia that we have reviewed are primarily concerned with rockbursts and gas outbursts in coal mines. In Australia these events do not occur at depths less than 180 m. The observations indicate that the events can occur both in association with pre-existing geologic features as well as undisturbed host rock. Thus, the West Cliff Colliery in New South Wales experienced over 107 outbursts (including both rockbursts and gas bursts) up to 1983, all of which were associated with sills, dykes, or faults. In contrast, the Leichhardt Colliery in Queensland has experienced over 200 outbursts during the same time period with only one being associated with an existing fault. Thus, differences are observed in the induced events even though the mining is largely conducted at the same depths (400 to 500 m) and the horizontal stresses are similar.

Although there are differences, the descriptions of the genesis of the outbursts in both these cases is consistent with the model for the generation of rockbursts described above. In the case of the West Cliff events, outbursts occurred as the mining face approached an existing fault. In the case of the Leichhardt Colliery, outbursts occurred when so-called "stable" cracking temporarily stopped. Thus, the slow deformation of the surrounding rock could not compensate for the change in stress energy caused by the removal of rock. This resulted in large stress concentrations near the ends of the mining face and an outburst occurrence.

2.7 Rockbursts in South Africa

Literature concerning rockbursts in South Africa is very extensive (e.g. Gane et al., 1946, 1952; Cook, 1963, 1976; Fernandez, 1973; McGarr et al., 1975, 1989, 1990) primarily due to the extreme hazard that such events pose to deep gold mining operations there. Prior to large-scale gold mining development, there was no history of felt seismic activity in the mining districts of South Africa (cf. Fernandez and Guzman, 1979). Figure 3 shows the seismicity in southern Africa reported in the CSS event catalog for the 20-year period from 1966 to 1985. The map shows a heavy concentration of events in the deep, gold-mining area surrounding Johannesburg, bounded approximately by 26° to 28°S and by 26.5° to 29.5°E. During a nine-year period from 1971 to 1979, annual event catalogs published by the Geological Survey of South Africa show about 85 events per year occurring within the mining area with magnitudes in the range from 3.4 to 5.9 M_L. The large number of rockbursts occurring in the gold-mining district of South Africa makes this a valuable source of data for seismic identification studies. In particular, the frequent occurrence of large events (viz magnitudes near 5) enables study of the characteristics of these induced events at ranges beyond those used in regional monitoring, unlike most other rockburst areas. Furthermore, the extensive literature based on investigations of South African rockbursts enables a better understanding of the mechanisms for the events in this source area.

The operating level in most South African gold mines is between two and four kilometers below the surface. As a result, many South African rockbursts occur at depths below those in most other mining areas. The common mining practice of stoping causes failure of the rock in the regions of maximum stress concentration near the edges of the excavation. This failure produces nearly continuous seismic activity on these new fracture planes which are approximately parallel to the stope face and normally located within tens of meters of the advancing mining activity. In-situ stress measurements from these mining areas most frequently show a nearly vertical pressure axis (cf. Gay, 1975, 1977) and horizontal tension with somewhat variable orientation. Consequently, rockburst mechanisms are frequently normal dip-slip.

Comparisons of the rate of rockburst occurrence with the rates at which material is removed from the mines indicates a very high correlation for South African mines.

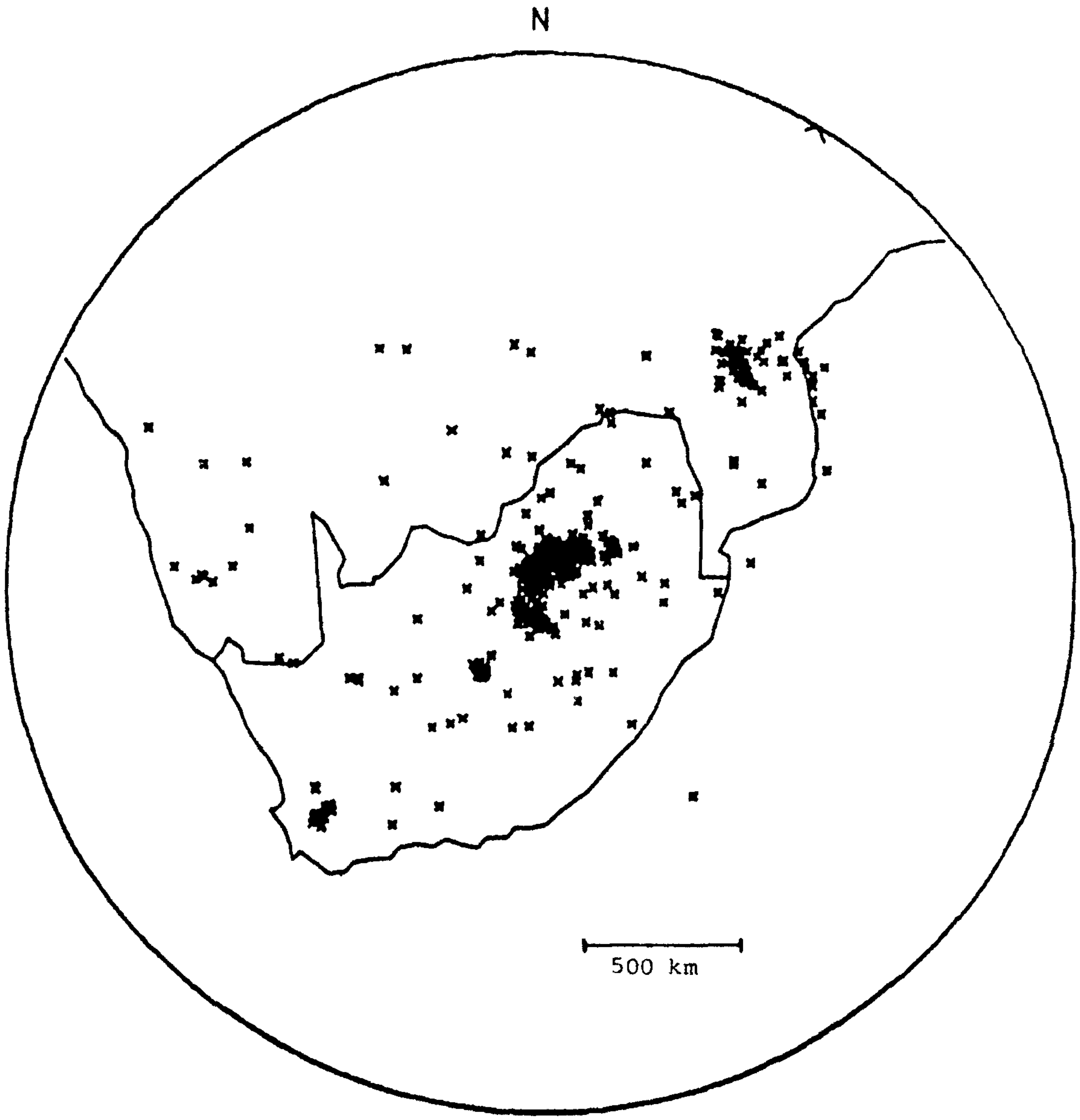

Figure 3. Seismicity in southern Africa for the period 1966-1985. Azimuthal equidistant projection centered on heavy concentration of rockbursts at 27°S, 27°E.

Gay, et al. (1983) found that in the Klerksdorp district the number of rockbursts per month closely tracked the area mined. For example, in mid-1978 5000 centares were mined per month, and the rockburst rate was more than 30 events per month. However, in mid-1979, when the mining rate was only about 2000 centares per month, the number of rockbursts was less than 10 per month. This appears to corroborate the evidence cited above for other mining regions.

2.8 Rockburst Control in Zambia

Several case histories suggest that mining practice may be modified to control rockburst occurrence. One of the more successful programs of this type was reported by Russell et al. (1983) for the Mufulira copper-mining district Zambia. An extensive measurement and analysis program was undertaken there to formulate a mining plan which would permit extraction of the copper without undue hazard from rockbursts. A 3-D finite element code was used to calculate stresses in the orebody and for the region where the hanging wall and footwall converge. These results were combined with additional 2-D finite element analyses for development areas near the stope face and crosscuts. Predictions were tested and refined based on observations and in-situ measurements, and finally very precise criteria were developed for determining a higher stress threshold which would cause rockbursts, an intermediate level which might produce spall, and a low level causing only minor flaking. The mining strategies which have been used in development since the late 1970's were designed to avoid bringing stress to the critical rockburst level and have apparently been successful.

2.9 Summary of Rockburst Observations

In summary, rockbursts or induced seismic activity occur in mining areas throughout the world. Magnitudes of individual seismic events are normally small (less than about 3 M_L) but have occasionally exceeded magnitude 5 M_L in some areas. The occurrence of such events in different areas appears to involve some common factors; but there are also elements in the observations unique to specific mining regions. Factors affecting rockburst occurrence include depth of mining activity, strength of the rock adjacent to the excavation, presence of preexisting zones of weakness in the rock, and tectonic stress conditions in the region of the mine. In addition, parameters related to mining practice such as rate of material removal, areal extent of the excavation, and other mine geometry (e.g. room-and-pillar versus long-wall) influence the size, frequency, and mechanism of the induced seismic events. As a result, variations in the seismic signals from rockbursts can be expected between different mining regions and possibly between events within a mining district if mining practice is varied.

III. Seismic Data from Regions of Rockburst Events

3.1 Database Development

Because of the small magnitudes of most rockburst events, the most useful seismic data for their analyses is frequently the signals recorded at regional stations. Only relatively large rockbursts ($m_b \cong 5$) produce strong signals at high-quality, non-array stations at teleseismic ranges. For this study we have sought to identify high-quality regional seismic data for several areas of known rockburst activity. In an effort to characterize the teleseismic signals from rockbursts, we have also obtained recordings at more distant stations from several larger events. The database currently includes digital waveforms from over 100 events from known rockburst source regions; many of the events have been recorded at multiple stations. The data collection effort has focussed primarily on two source areas: South Africa and Central Europe. As described in the previous section, each of these areas has a long history of rockburst occurrence which has included large events.

It should be noted that, in designating events as rockburst for use in this study, we only rarely have corroborative information of source type. The inference that events are rockbursts is based on the fact that the events are located in mining areas dominated by the occurrence of induced events. In most of these areas there was little or no evidence of natural seismic activity prior to mine development. Furthermore, blasting for mine development is either not used or has only very low energy release at these below-surface mines. As a result it is unlikely that mineblasts or natural earthquakes are misdesignated as rockbursts for use in this study. In some source areas larger blasts may be used in surface quarrying or strip mining. However, the locations for such activity are usually fairly well-defined; and we have attempted to avoid such areas in identifying potential rockbursts for this research. Events designated as blasts or earthquakes, used for comparison purposes in this study, usually have been identified as such in prior reports by some other authority.

For our initial analyses we have focussed on digital data recovered from the GDSN/SRO database at the DARPA Center for Seismic Studies and for more recent events data have been obtained from the IRIS Data Management Center. We have also used data obtained for several events recorded during a six-week period in the Spring of 1991 for the Group of Scientific Experts Second Technical Test (GSETT-2). In general, we have attempted to retrieve all available short-period and broad-band data with sampling rates of 20 samples per second or greater for all the stations in these databases. For use in analyzing long-period surface-wave excitation, we have also obtained lower sampling-rate data for several events at selected stations. Source parameters for most of the events in this study were obtained from NEIS/USGS, South African or Grafenburg bulletins or occasionally other published reports. For regional stations the data windows included P and L_g segments, while teleseismic stations and far-regional stations were limited to P and long-period surface-waves at selected stations. As this research continues we hope to draw upon additional data sources including high-quality array stations (e.g. AEDS and NORSAR).

3.2 Data from South African Events

The current database for South Africa includes 69 events. The epicenter locations for these events are plotted in Figure 4. Fifty-one of the events have locations in proximity to the deep gold-mines of the Witwatersrand basin near 27°S 27°E. These events are presumed to be mine tremors, or rockbursts. As can be seen on the map, the mining events cluster in three or four distinct subareas apparently associated with specific mines. The remaining eighteen events are dispersed outside the principal mining area and are, therefore, presumed to be either natural earthquakes or surface mine explosions. Table 3 summarizes the source parameters for the events in Figure 4. Magnitudes for most of the smaller events are reported as M_L and as m_b for most of the large events. The events cover a magnitude range from about 2.3 to 5.2 m_b. Events in the areas where mine tremors are known to occur are identified as probable rockbursts (prb). Events from outside the principal rockburst areas are designated as earthquakes (eqk) although some of the smaller events might also be blasts at surface mines. Figure 5 shows the locations of seismic stations for which we have identified detectable signals from at least some of the South African events. The station distances range from less than 1° to SLR, located in the midst of the South African mining activity, to CTAO, in Australia, at nearly 105°. Because of its proximity to the source area, DWWSSN station SLR records regional signals with fairly strong signal-to-noise levels from even relatively small rockbursts. Unfortunately, large events tend to be clipped at

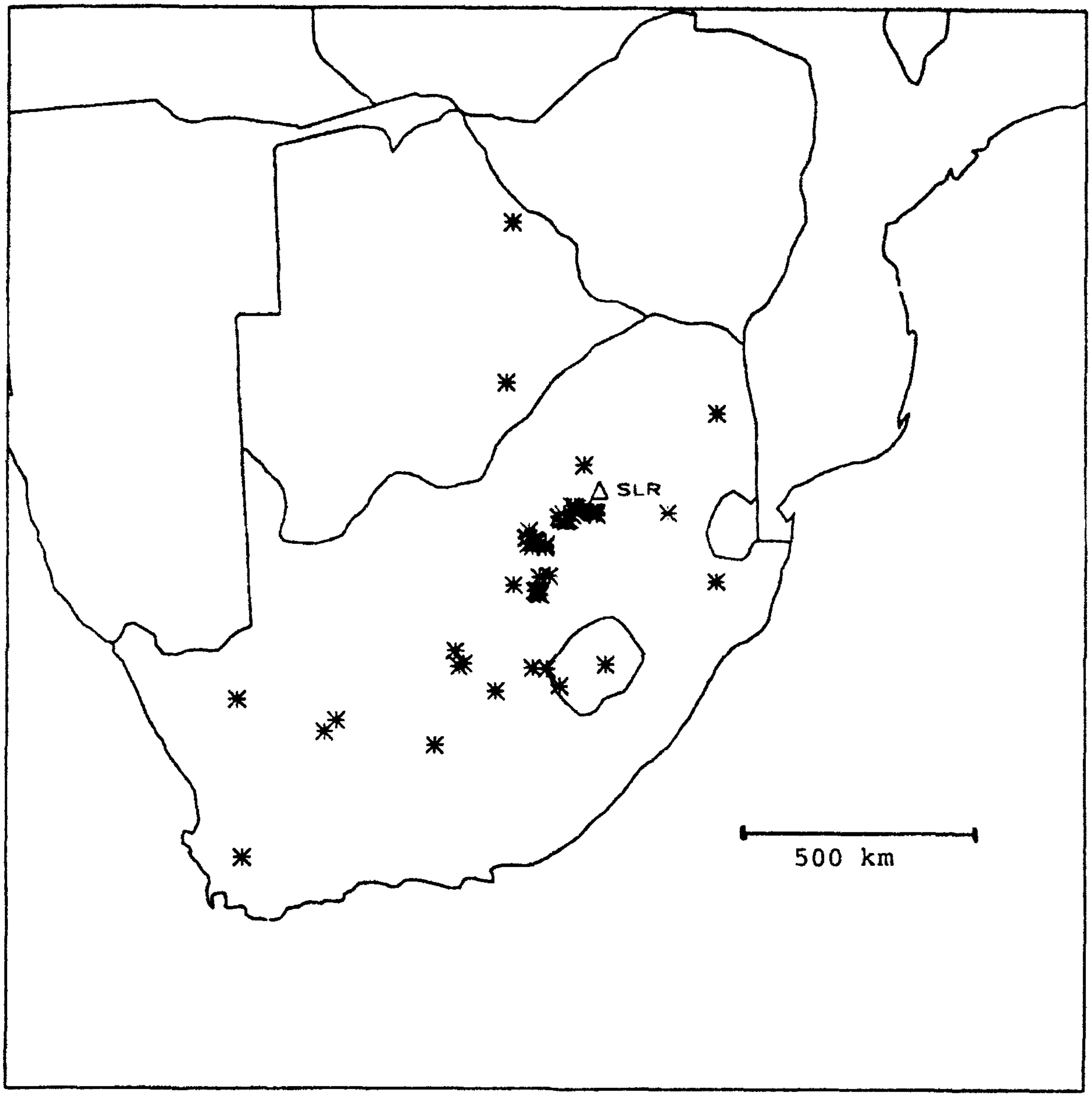

Figure 4. Locations of rockbursts and other events in southern Africa currently in the database.

Table 3. South African Events in Current Database

Date	Origin Time	Lat (S)	Lon (E)	Mag	ID
01/28/80	06:30:57	26.396	27.463	4.5	prb
02/09/80	13:51:10	27.802	26.235	5.2	prb
02/17/80	21:01:22	27.627	26.865	4.7	prb
03/22/80	02:14:10	26.120	27.752	5.2	prb
04/03/80	22:45:38	26.081	27.703	4.8	prb
04/08/80	00:39:35	26.293	27.653	4.2	prb
05/06/80	21:07:25	26.926	26.998	4.6	prb
06/12/80	03:03:42	26.991	26.991	4.8	prb
06/13/80	21:15:03	26.845	26.769	4.8	prb
01/28/81	16:20:33	26.073	27.611	4.6	prb
02/18/81	08:28:20	26.625	26.607	4.7	prb
11/05/81	20:19:31	29.950	27.370	4.0	eqk
11/19/81	17:19:42	28.000	26.840	3.6	prb
11/22/81	03:31:27	26.400	27.500	3.6	prb
11/22/81	05:15:59	26.380	27.570	3.3	prb
11/26/81	07:16:49	24.080	30.980	3.2	eqk
12/01/81	09:04:34	25.207	27.912	3.3	prb
12/01/81	15:11:45	26.400	27.370	3.3	prb
12/14/81	14:41:01	26.320	27.330	4.0	prb
12/15/81	14:11:15	27.600	27.100	4.7	prb
12/15/81	16:29:49	26.360	27.530	3.0	prb
03/26/82	13:41:24	27.660	31.100	4.3	eqk
03/28/82	15:51:37	26.270	28.220	4.1	prb
04/01/82	07:11:01	30.040	19.400	3.4	eqk
04/02/82	12:57:09	26.830	26.750	3.2	prb
04/02/82	20:08:54	26.220	28.090	3.0	prb
04/09/82	01:52:37	26.800	26.600	3.9	prb
04/13/82	11:26:00	27.920	26.780	5.0	prb
04/13/82	11:26:51	27.900	26.800	4.6	prb
05/09/82	07:07:02	29.600	27.060	3.4	eqk
06/07/82	00:56:30	27.900	26.800	3.9	prb
06/16/82	17:57:22	23.500	26.100	-	eqk
06/17/82	04:18:52	26.140	27.710	-	prb
06/27/82	00:36:36	26.760	26.540	3.6	prb
06/28/82	09:20:08	26.880	26.810	3.4	prb
09/01/82	11:38:20	27.930	26.830	3.7	prb
09/10/82	09:24:21	26.200	29.900	-	eqk
11/12/82	06:11:32	26.906	26.750	5.0	prb
12/02/82	20:45:34	30.600	21.800	3.2	eqk
12/11/82	22:03:04	26.900	26.600	3.9	prb
12/11/82	22:03:59	26.830	26.720	3.8	prb

Table 3. (Continued)

Date	Origin Time	Lat (S)	Lon (E)	Mag	ID
02/22/83	16:26:41	29.493	28.493	-	eqk
05/24/83	11:49:51	26.900	26.720	2.6	prb
05/24/83	13:09:57	27.990	26.800	3.2	prb
06/01/83	00:55:22	26.200	28.130	3.3	prb
06/03/83	16:13:59	26.220	28.150	2.3	prb
06/06/83	10:48:51	26.890	26.660	5.2	prb
07/17/83	13:38:07	26.140	27.890	2.8	prb
07/31/83	00:35:41	31.190	24.250	3.7	eqk
08/01/83	16:58:21	26.220	28.210	2.8	prb
08/04/83	06:05:48	33.390	19.270	-	eqk
08/26/83	21:19:26	30.830	21.500	2.7	eqk
08/26/83	21:29:49	26.350	27.320	2.7	prb
09/05/83	00:33:36	29.470	25.020	4.7	eqk
09/05/83	00:33:43	29.200	24.800	-	eqk
09/09/83	03:05:34	29.540	24.900	-	eqk
09/29/83	08:59:12	28.020	26.880	2.8	prb
10/01/83	04:43:13	26.190	27.700	-	prb
11/02/83	23:16:47	30.060	25.790	3.2	eqk
01/28/84	14:40:02	26.900	26.650	4.9	prb
03/21/84	16:47:58	26.190	27.850	2.9	prb
06/04/84	06:45:07	20.140	26.250	3.5	eqk
08/11/84	21:23:10	26.800	26.520	4.9	prb
08/19/84	15:31:52	29.580	26.710	-	eqk
01/01/86	16:00:50	26.780	26.600	4.9	prb
02/10/86	20:45:02	27.940	26.750	5.0	prb
08/11/86	04:59:10	26.920	26.570	4.9	prb
09/15/86	07:06:31	26.270	27.430	4.9	prb
10/28/86	15:04:21	26.980	26.680	5.2	prb

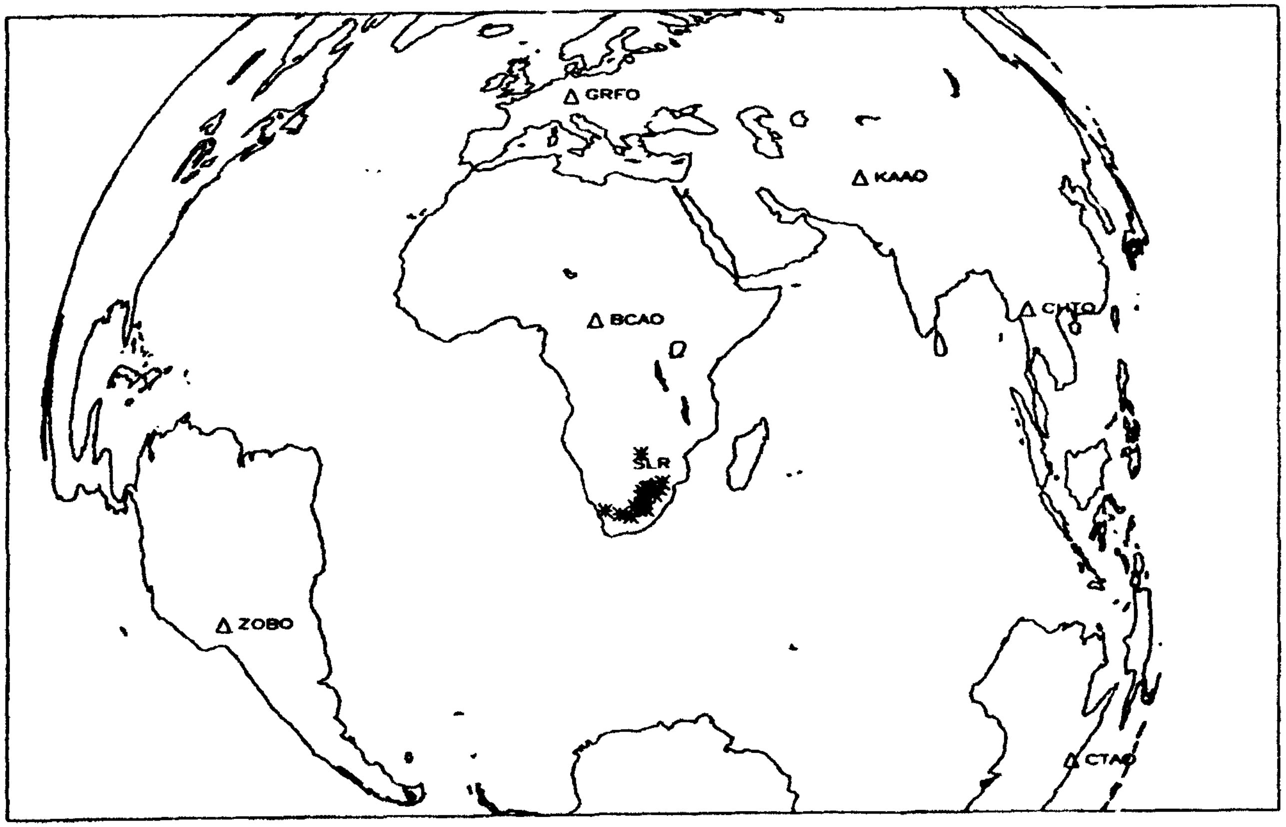

Figure 5. GDSN stations which frequently record identifiable signals from South African rockbursts. Azimuthal equidistant projection centered on 27°S, 27°E.

SLR due to the limited dynamic range of the DWWSSN recording system. At the opposite extreme, many of the teleseismic stations record signals above the noise level, and frequently trigger, for only the largest rockburst events. As a result, the South African rockburst database tends to be most complete at SLR for events with magnitudes below about 4.5 m_b; and at CTAO or CHTO ($\Delta \cong 83^o$) teleseismic P signals are barely discernible for events with magnitudes below about 4.8 m_b. For the teleseismic stations the database tends to be most complete for stations BCAO ($\Delta \cong 32^o$) and ZOBO ($\Delta \cong 87^o$). The latter station somewhat surprisingly records P signals with large signal-to-noise levels for many of the larger South African rockbursts even at its relatively large epicentral distance.

Figure 6 shows records from a sample of South African rockbursts recorded at station SLR. The signals are typical of seismic records from the near-regional to regional distance range, including multiple P phases, complex S and L_g windows, and short-period R_g in many cases. P_n and P_g phases are identifiable, particularly for the more distant regional events; and the strong fundamental mode Rayleigh wave (possibly controlled by the upper crustal sediments in the Witwatersrand basin) dominates the later part of the records. There are clear differences in the waveforms recorded at SLR between events from different mining areas. However, it is expected that the main differences in this case may be in large measure related to propagation path variations between events rather than to any changes in source mechanism. The regional signals tend to be separated into distinct phases for mining areas at somewhat greater distances instead of clumped and interfering for the nearest events. Range clearly appears to affect the relative amplitude between phases for these regional recordings. In addition to the rockbursts, our data sample at SLR includes apparent earthquakes or blasts in South Africa from outside the mining areas. More complete comparisons of relative amplitudes, spectral characteristics and possible discriminant measures of the regional phases from South African rockbursts and other event types are evaluated in Section IV of this report.

Records of the P-wave signals at station BCAO for a sample of South African rockbursts are shown in Figure 7. This station is located at Bangui in the Central African Republic at an epicentral distance range of about 32^o. These signals show a great deal of consistency from event to event. In general, the P-wave window is dominated by the initial P onset as is typical for teleseismic P. However, in some cases the P coda appears significantly more complex with one or more prominent secondary phases. The

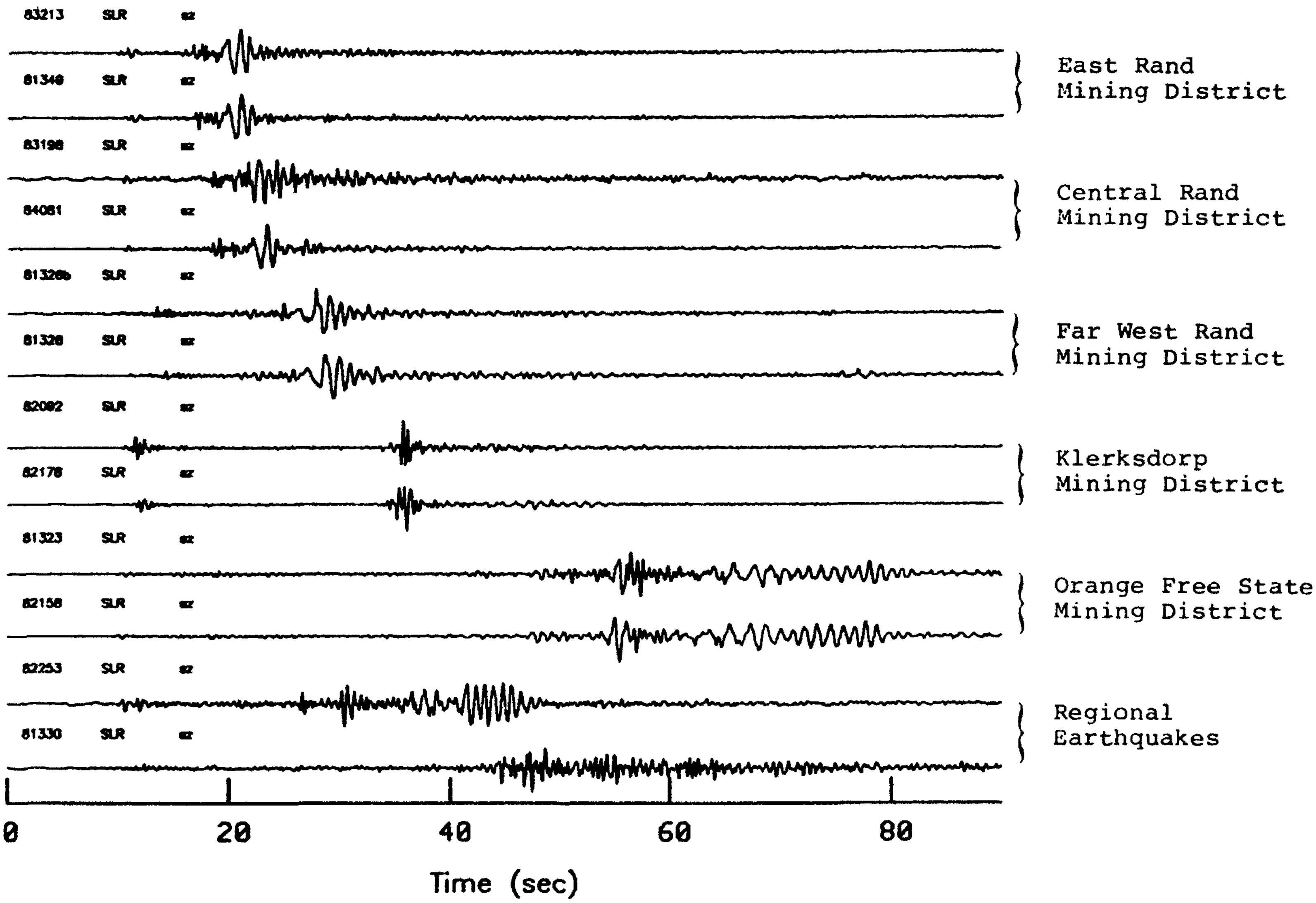

Figure 6. Examples of SLR short-period, vertical-component records from South African mine tremors in five different areas and two presumed regional earthquakes.

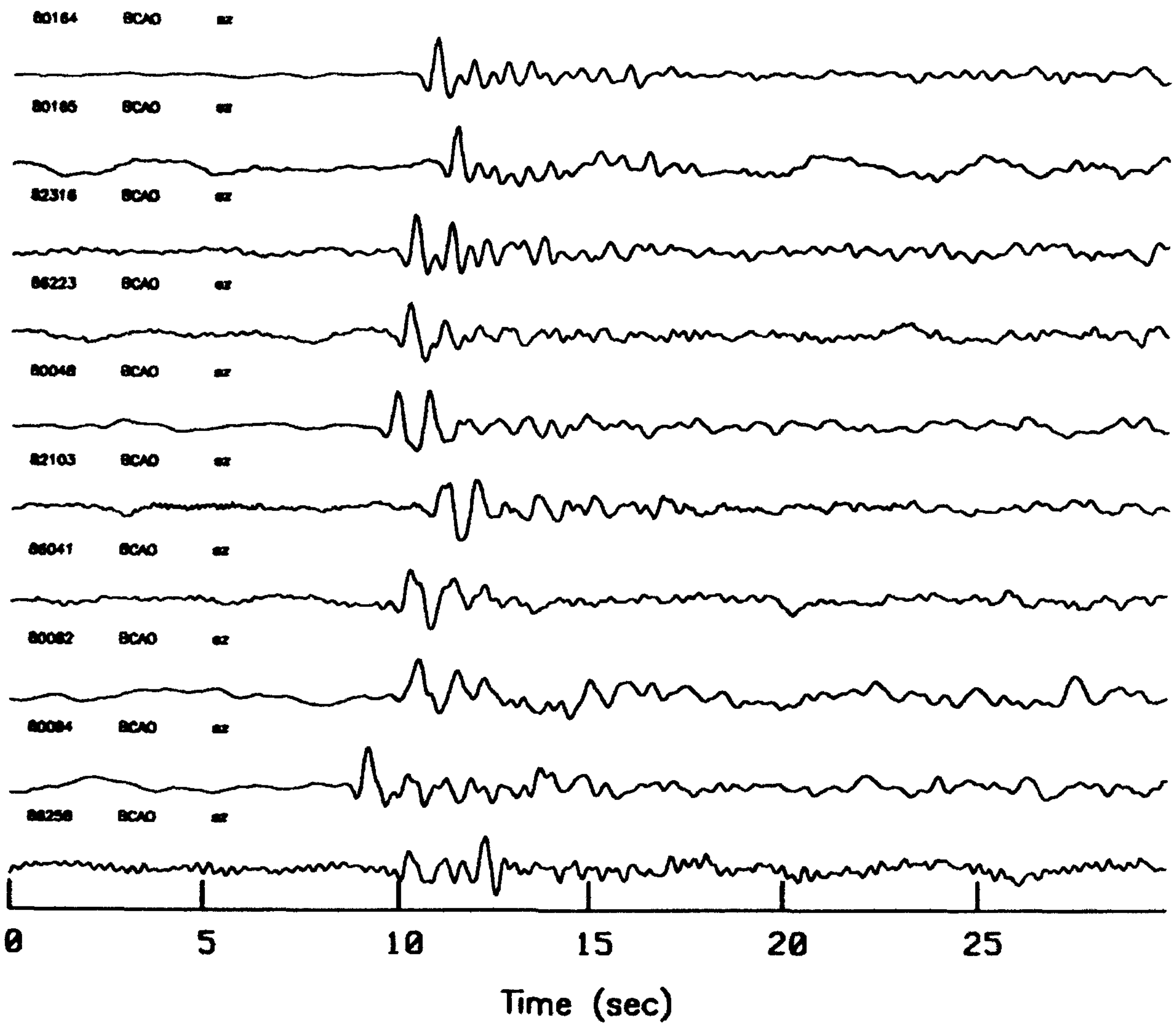

Figure 7. Examples of short-period, vertical-component P-wave signals at BCAO from large South African rockbursts.

fact that these secondary phases are not present on all records, even for events from the same mining area, suggests that this is not a propagation effect but rather represents added complexity in some sources. In fact, some events appear to contain multiple sources (e.g. compare the P signal from the 11/12/82 rockburst with that of the 06/13/80 rockburst in the same mining area). We will analyze possible evidence of source variability between events in Section IV of this report.

Figure 8 shows examples of the P-wave signals from South African rockbursts recorded at station ZOBO in the Zongo Valley of Bolivia. Even at this large epicentral distance of 87°, the P signals are strong and well above the noise level for these magnitude 5 events. The records again appear to be very consistent between events, somewhat independent of differences in the mining area of the source. In this case the strong appearance of consistency in the teleseismic signals between events may be associated with a station crustal site response which produces ringing in the P wave. This apparent P-wave reverberation tends to mask differences in the signals which may be associated with source variations between events. In the analyses of the following section of this report, we have attempted to get around this difficulty by comparing P-wave spectral ratios.

For the South African rockbursts, Figures 9 and 10 illustrate the typical character of the signals at some of the most distant stations, CHTO in Thailand ($\Delta \cong 83^{\circ}$) and CTAO in Australia ($\Delta \cong 105^{\circ}$), respectively. The teleseismic P-wave signals at other stations, including TOL in Spain ($\Delta \cong 73^{\circ}$), KAAO in Afghanistan ($\Delta \cong 73^{\circ}$), and GRFO in Germany ($\Delta \cong 78^{\circ}$), are similar in character to those presented here. Only rarely were the GDSN recording systems triggered at these stations and then only for the largest magnitude rockbursts. For the magnitude 5 events shown, the teleseismic P signals are typically weak and just above the background noise levels at these distant stations.

Finally, we have also attempted to collect long-period seismic data for selected stations from South African events. Figure 11 shows representative long-period data from station BCAO ($\Delta \cong 32^{\circ}$) for several rockbursts. The mark on the records indicates a group velocity of 3 km/sec corresponding to the expected approximate arrival time of the long-period, fundamental-mode Rayleigh wave. The actual arrival time may vary slightly depending on crust and upper-mantle structure along the transmission path. Although there appear to be clear indications of the presence of the long-period Rayleigh phase on the records for these rockbursts down to magnitude levels below 4.5 m_b,

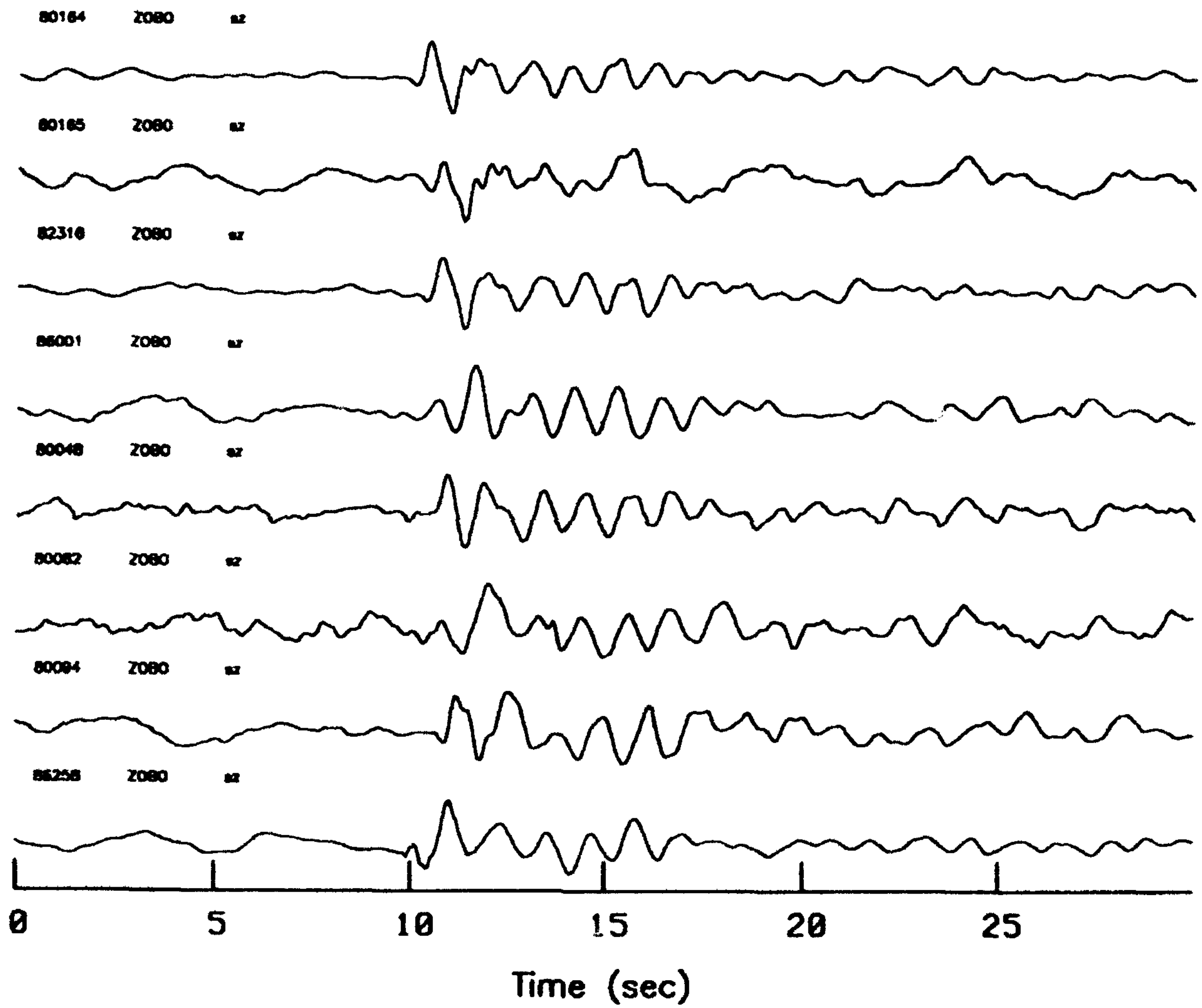

Figure 8. Examples of short-period, vertical-component P-wave signals at ZOBO from large South African rockbursts.

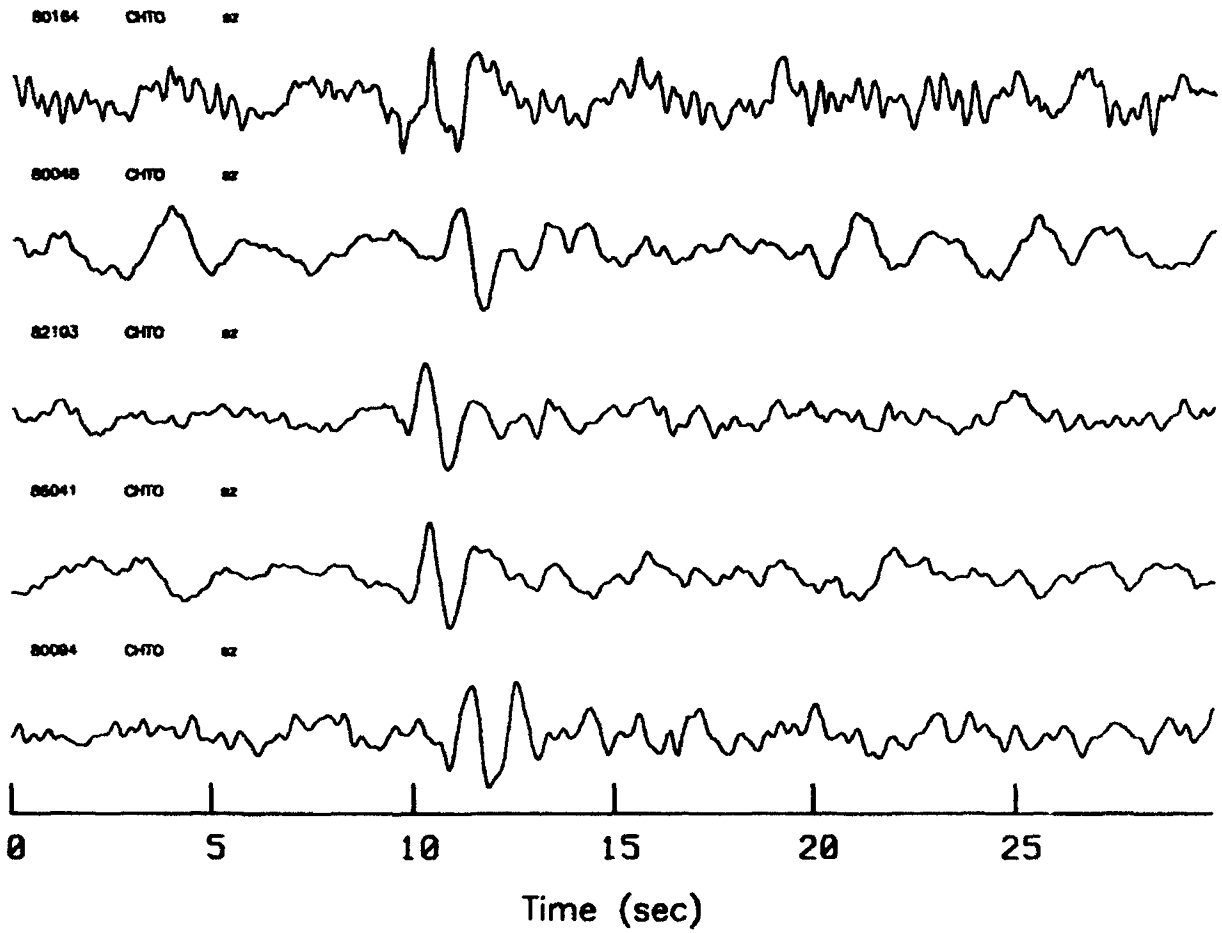

Figure 9. Examples of short-period, vertical-component P-wave signals at CHTO from large South African rockbursts.

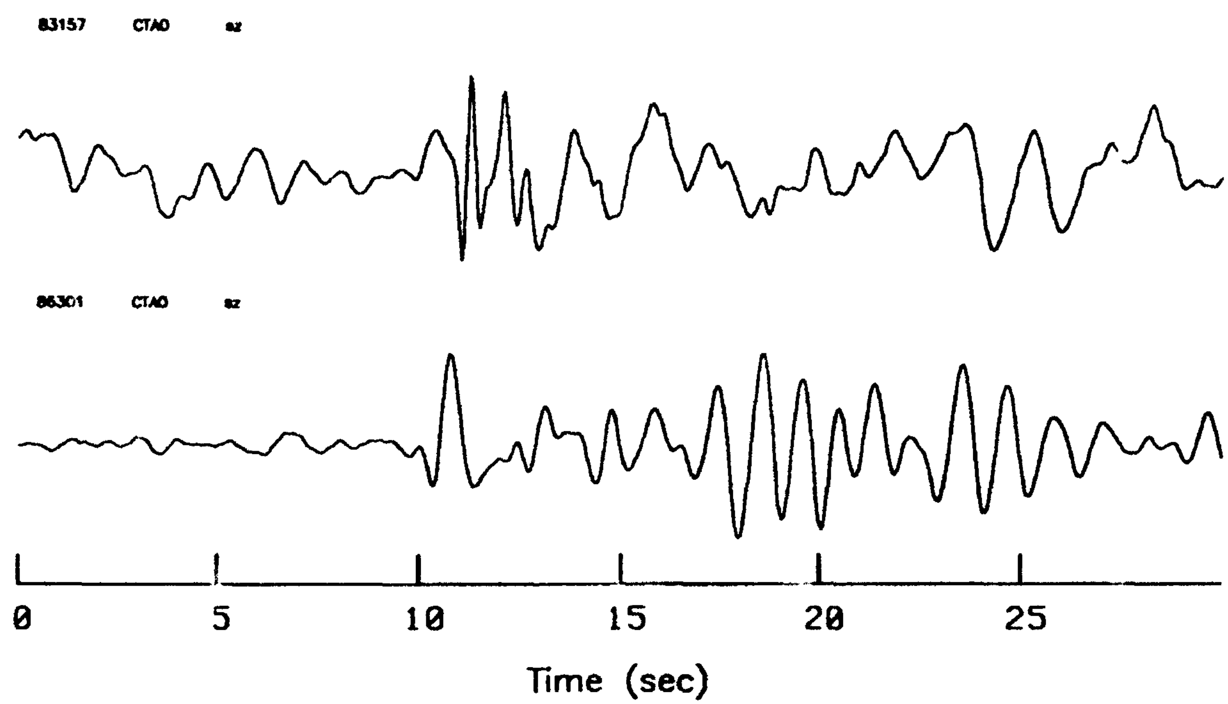

Figure 10. Examples of short-period, vertical-component P-wave signals at CTAO from large South African rockbursts.

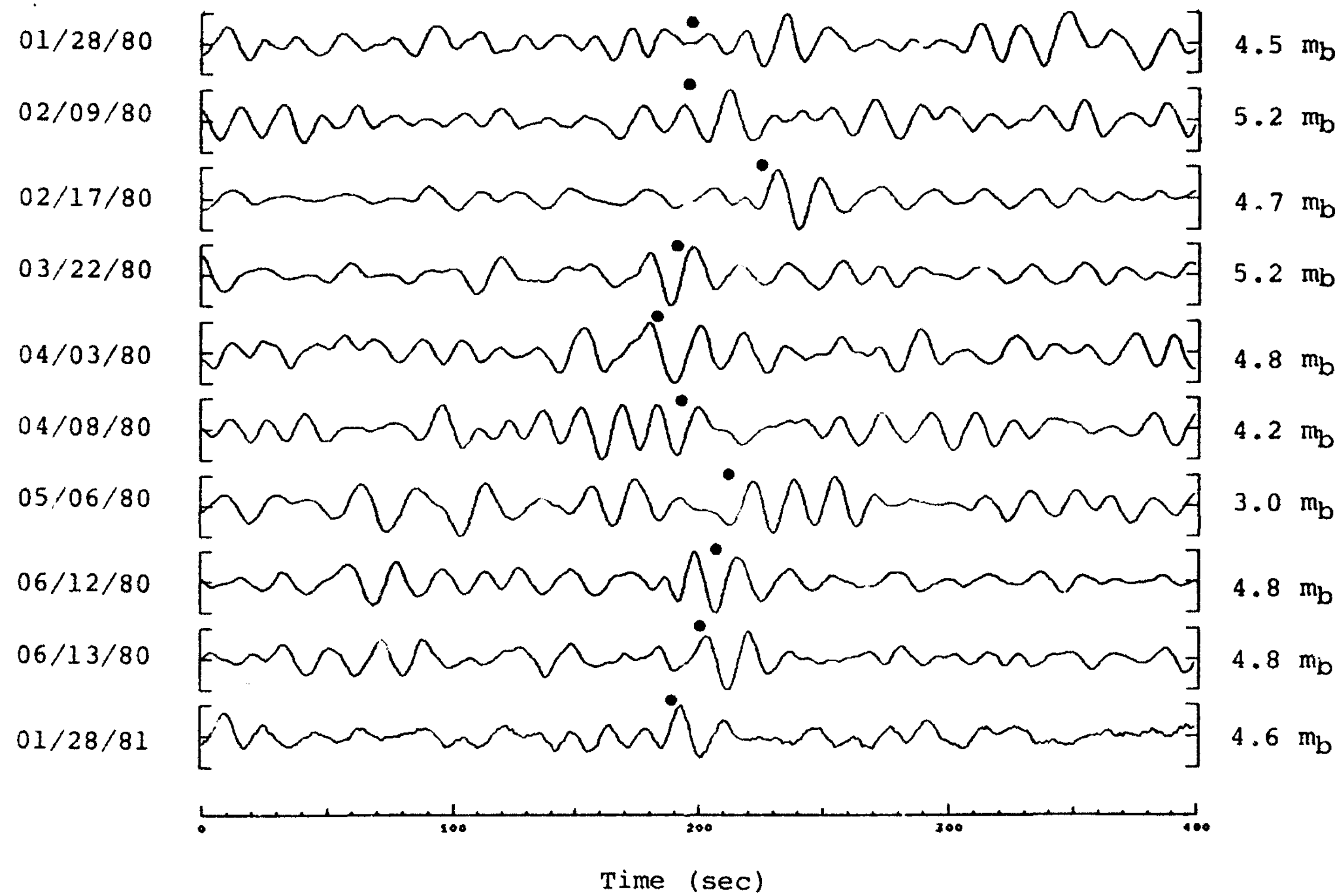

Figure 11. Examples of BCAO long-period, vertical-component records from large South African mine tremors.

signal-to-noise levels are not much above one. As a result, we would not expect to see much of the long-period signals from rockbursts at stations at larger ranges unless noise conditions are unusually low or some techniques for signal enhancement may be used.

In summary, for the GDSN database the best available seismic data for South African rockbursts come from the regional station at SLR and a few teleseismic stations, BCAO and ZOBO, which appear to have favorable transmission paths. In addition to the rockbursts, our database currently includes a sample of events from outside the mining areas which may be useful in helping to discriminate between different event types.

3.3 Data from Central European Events

The induced seismic events from the Central European region are most often not as large as many South African mine tremors. As a result, regional seismic data are even more critical for analyses of rockburst events from this source region. For Central Europe our current database includes 44 events. The locations of the epicenters of these events are plotted in Figure 12. The majority of the events (~ 38) are clustered in two areas of Poland near the Czechoslovakian border: one centered near 51.1^{o}N 15.8^{o}E, and the other near 51.0^{o}N 19.0^{o}E. The former corresponds to the copper mining region near Lubin, and the latter is a coal mining area in Upper Silesia. Both of these areas are known to be places where there has been considerable induced stress release (rockbursts) associated with mining. The remaining six events include three events thought to be rockbursts in other areas, two natural earthquakes and one small quarry blast. Table 4 summarizes source parameter information regarding the events plotted in Figure 12. The events have magnitudes between about 2.1 and 5.4 m_b. For these Central European events we have initially concentrated on retrieving data from station GRFO, the closest GDSN station to the source areas with ranges from 3^{o} to 5^{o} However, we also found waveform data for several of these events at a few additional GDSN stations, including KONO ($\Delta \cong 10^{o}$), TOL ($\Delta \cong 20^{o}$) and BCAO ($\Delta \cong 46^{o}$). Figure 12 shows the locations of these GDSN stations relative to the source area. In addition, the Central European events which occurred during the GSETT-2 experiment were recorded by an extensive network of European and Scandinavian stations (cf. Figure 13). Since the events in this latter data sample tend to be more scattered, distances to the

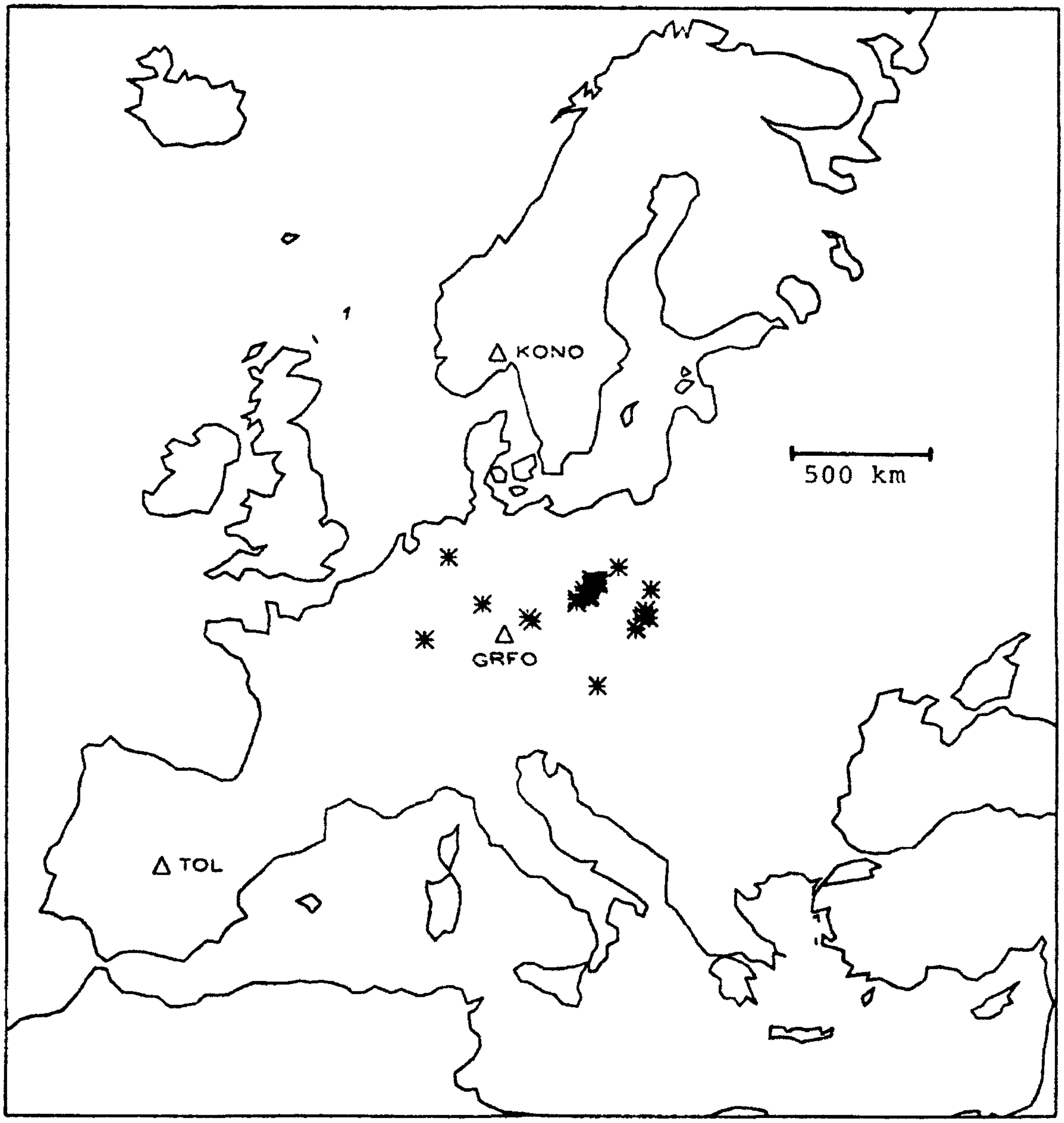

Figure 12. Locations of rockbursts and other events in central Europe currently in the database.

Table 4. Central European Events in Current Database

Date	Origin Time	Lat (N)	Lon (E)	Mag	ID
08/15/80	20:03:04	51.153	15.892	3.6	prb
08/25/80	00:40:48	51.115	15.745	3.3	prb
09/14/80	15:39:13	51.623	16.200	3.6	prb
09/30/80	01:02:00	50.350	18.910	-	prb
10/02/80	17:23:44	51.319	15.571	3.9	prb
10/09/80	04:46:59	51.095	15.687	3.4	prb
11/29/80	20:42:00	51.250	19.400	-	prb
12/21/80	05:51:16	51.633	16.259	4.2	prb
12/23/80	21:10:30	51.636	16.375	3.7	prb
04/10/81	04:59:47	51.630	16.180	4.3	prb
07/12/81	11:59:26	50.522	19.012	4.1	prb
08/02/81	03:25:16	50.254	18.779	-	prb
08/11/81	23:48:06	49.861	18.425	4.1	prb
08/15/81	05:40:14	51.457	15.954	4.0	prb
08/19/81	12:41:25	52.103	17.574	3.4	prb
09/23/81	23:53:41	51.153	15.818	2.8	prb
11/03/81	05:42:44	51.027	15.867	3.7	prb
11/25/81	10:14:20	51.055	15.828	3.9	prb
12/11/81	02:02:32	51.161	15.817	3.9	prb
01/16/82	11:15:59	51.610	16.281	4.2	prb
01/22/82	03:09:03	51.156	15.516	3.4	prb
03/19/82	14:48:05	50.988	15.155	3.3	prb
04/12/82	12:45:37	51.512	15.966	3.4	prb
04/18/82	06:42:16	51.651	16.085	3.5	prb
04/22/82	21:22:38	51.153	15.860	3.3	prb
05/23/82	18:22:41	50.851	15.158	3.3	prb
06/04/82	10:44:34	50.537	19.062	4.6	prb
06/08/82	15:48:29	51.444	15.961	4.0	prb
06/08/82	16:33:40	51.156	15.831	3.4	prb
06/13/82	21:15:27	51.689	15.946	4.1	prb
06/15/82	20:00:59	51.620	16.278	3.7	prb
06/17/82	09:30:42	49.915	18.470	3.8	prb
06/19/82	23:36:29	51.532	15.986	3.7	prb
07/14/82	00:56:37	51.681	16.098	4.0	prb
03/13/89	13:02:15	50.710	9.900	5.2	rb
04/30/91	03:40:39	51.542	16.227	3.3	prb
05/02/91	10:15:20	47.962	16.204	4.3	eqk
05/16/91	02:06:17	52.281	7.761	4.4	prb
05/16/91	10:44:58	49.288	6.930	3.0	prb

Table 4. (Continued)

Date	Origin Time	Lat (N)	Lon (E)	Mag	ID
05/19/91	03:22:13	50.312	12.441	2.8	eqk
05/21/91	16:49:09	50.260	19.220	3.1	prb
05/23/91	19:42:56	51.583	16.085	3.1	prb
05/26/91	19:42:55	50.183	12.715	2.0	mb
05/28/91	03:52:50	51.528	16.392	3.4	prb

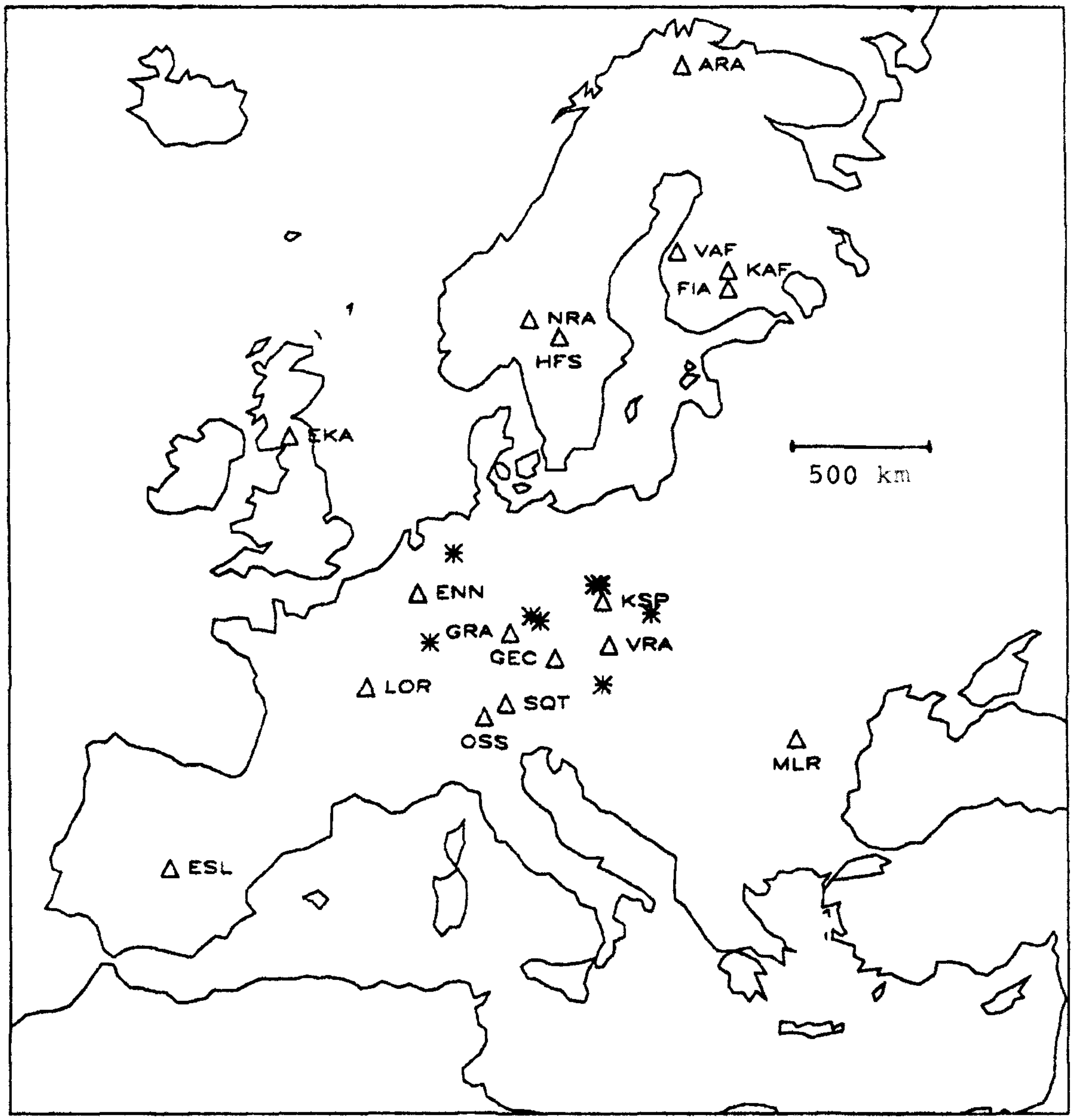

Figure 13. Locations of rockbursts and other events in central Europe recorded by GSETT-2 stations.

individual recording stations tend to be more variable between events. For both the GDSN and the GSETT-2 data, the seismic signals are usually strong and clear at the nearest stations; but, for smaller events and more distant stations, the signals are frequently at or barely above the background noise levels. In fact, except for GRFO the GDSN waveform data for Central European rockbursts show no evidence of P signals and only slight indications of signals in the predicted L_g group velocity windows. We have generally tried to focus on recordings with good signal-to-noise levels for these initial studies and have concentrated our analyses, therefore, on GRFO and GSETT-2 data for the Central European events.

Figure 14 shows GRFO vertical-component waveforms for a sample of presumed rockbursts from the Lubin and Upper Silesia areas of Poland. The epicentral distance range to the former source area averages about 410 km and to the latter about 560 km. For a given source area, the records at GRFO in general appear to be quite consistent from event to event. However, there are some clear differences between the two source areas. The strongest seismic phase on the GRFO recordings from each of the two source regions is L_g, which appears as a dispersed wavetrain with a duration between about 50 and 75 seconds. The relatively large L_g/P amplitude ratios for nearly all these *rockburst* events are similar to those seen for natural earthquakes in many areas. This behavior has been proposed over the years by various authors as a potent*ial regional* discriminant measure to distinguish such sources from explosions. The biggest difference in the records between the two source areas is the relative strength of the P phases. For the nearer source area (around Lubin), the P_g signal is quite clear in most cases, appearing as a dispersed segment with a duration of about 10 seconds. However, for the farther source region (Upper Silesia), the P_g signal is relatively weaker and sometimes barely emerges above the noise. The P_n phase is frequently clear for events in the nearer source area, arriving about 12 seconds prior to P_g. However, for the farther source area, P_n is most often lost in the noise prior to P_g and only rarely can be detected about 20 seconds before the P_g arrival. It is not yet clear to what extent these kinds of differences can be explained as propagation effects due to greater attenuation of the P phases to the more distant stations or whether some source mechanism difference might also contribute to the observed behavior. In Section IV of this report we will analyze such variations between source regions and between sources within a single area and assess their influence on possible discriminant measures.

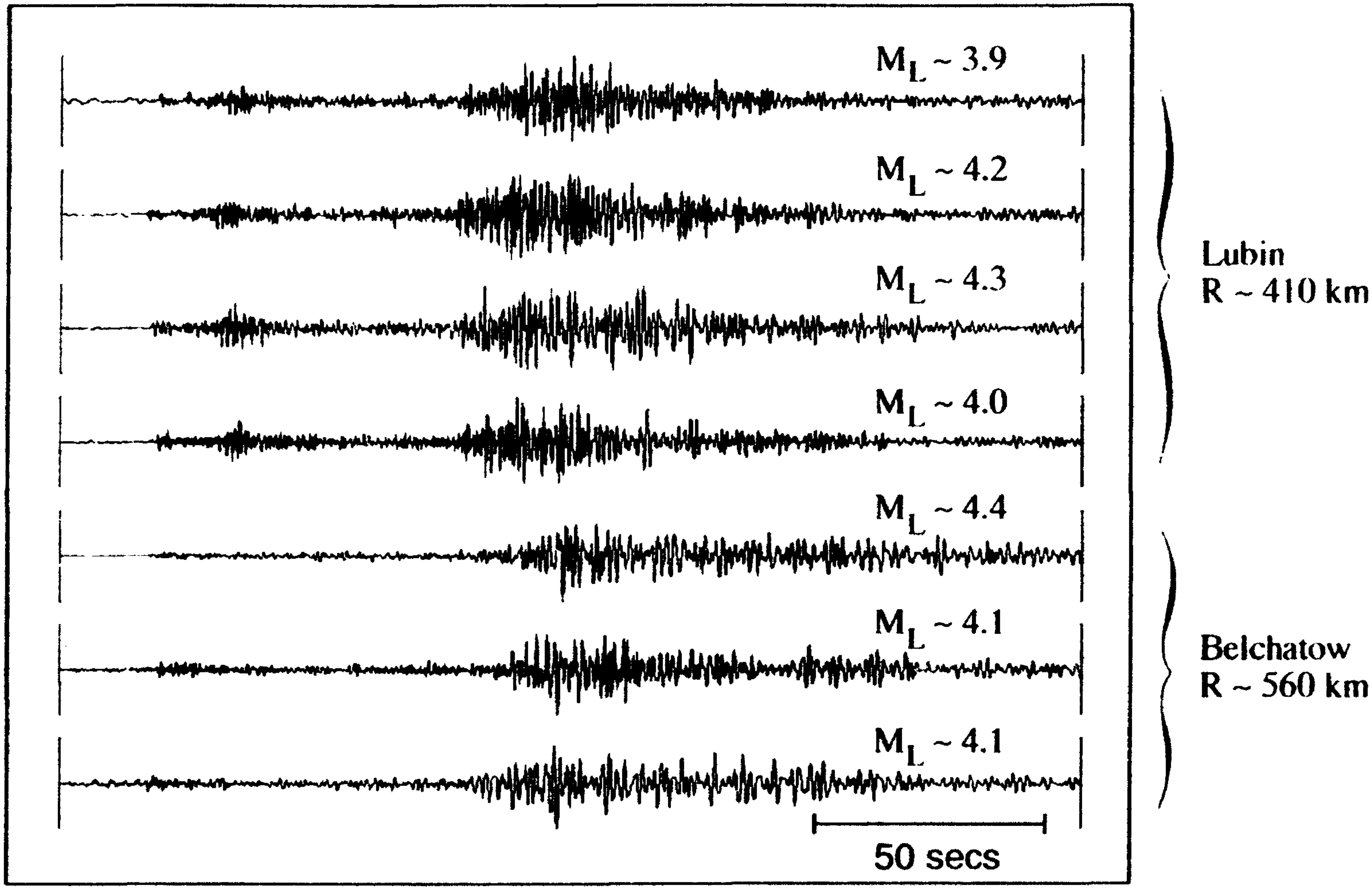

Figure 14. Examples of GRFO short-period, vertical-component records from rockbursts in the Lubin and Upper Silesia (Belchatow) mining areas.

Figures 15 and 16 show the vertical-component waveforms from two of the better recorded Central European events in the GSETT-2 data set. The first event occurred on May 16, 1991 near Ibbenburen, Germany with a magnitude of 4.4 M_L and is suspected of being induced because of its close proximity to deep coal mining operations (cf. Gestermann et al., 1992). The regional signals are strong at most stations within about 10° of the event; and there even appears to be a teleseismic P signal for this event at array station YKA in Canada at a range of 57°. In fact, at several of the stations nearest the source, the large regional phases from these events were clipped due to limitations on the dynamic range of the recording systems. It is difficult to compare regional signal characteristics between the GSETT-2 stations because of non-uniformity of instrument response and recording equipment. The waveforms at some of the regional stations do not extend through the complete L_g window, but where they do the L_g is clearly the dominant phase on the records. Time-domain L_g/P amplitude ratios are normally greater than two; but there are variations in the ratios between stations which could be related to either station response variations or possibly source effects. The waveforms in Figure 16 correspond to a natural earthquake in Austria with a magnitude of 4.3 M_L. Regional signals are again strong out to about 10° from the source; and there is also some evidence of a teleseismic P detection at station YKA at 63° from the source. L_g signals again tend to dominate the regional waveforms, being clipped at some of the nearer stations. Overall, the time-domain L_g/P amplitude ratios appear somewhat larger for the earthquake than for the rockburst in Figure 15; but this may represent a propagation effect since the source locations are significantly different. In the following section of the report, we will look further at differences between the regional signals which may be related to source type; and we will consider the merit of multiple recording stations surrounding the source.

In summary, the only GDSN station of practical value for monitoring most of the small rockburst events in Central Europe appears to be GRFO. However, waveform data from several other stations obtained during the GSETT-2 experiment also provide a valuable source for investigating identification techniques for events in Central Europe. Our database currently includes rockbursts, earthquakes and a quarry blast which are well-recorded by regional stations. We are also in the process of acquiring more complete seismic data from regional and more distant digital stations for a large rockburst (viz March 13, 1989 in Germany) and a large earthquake (viz April 13,

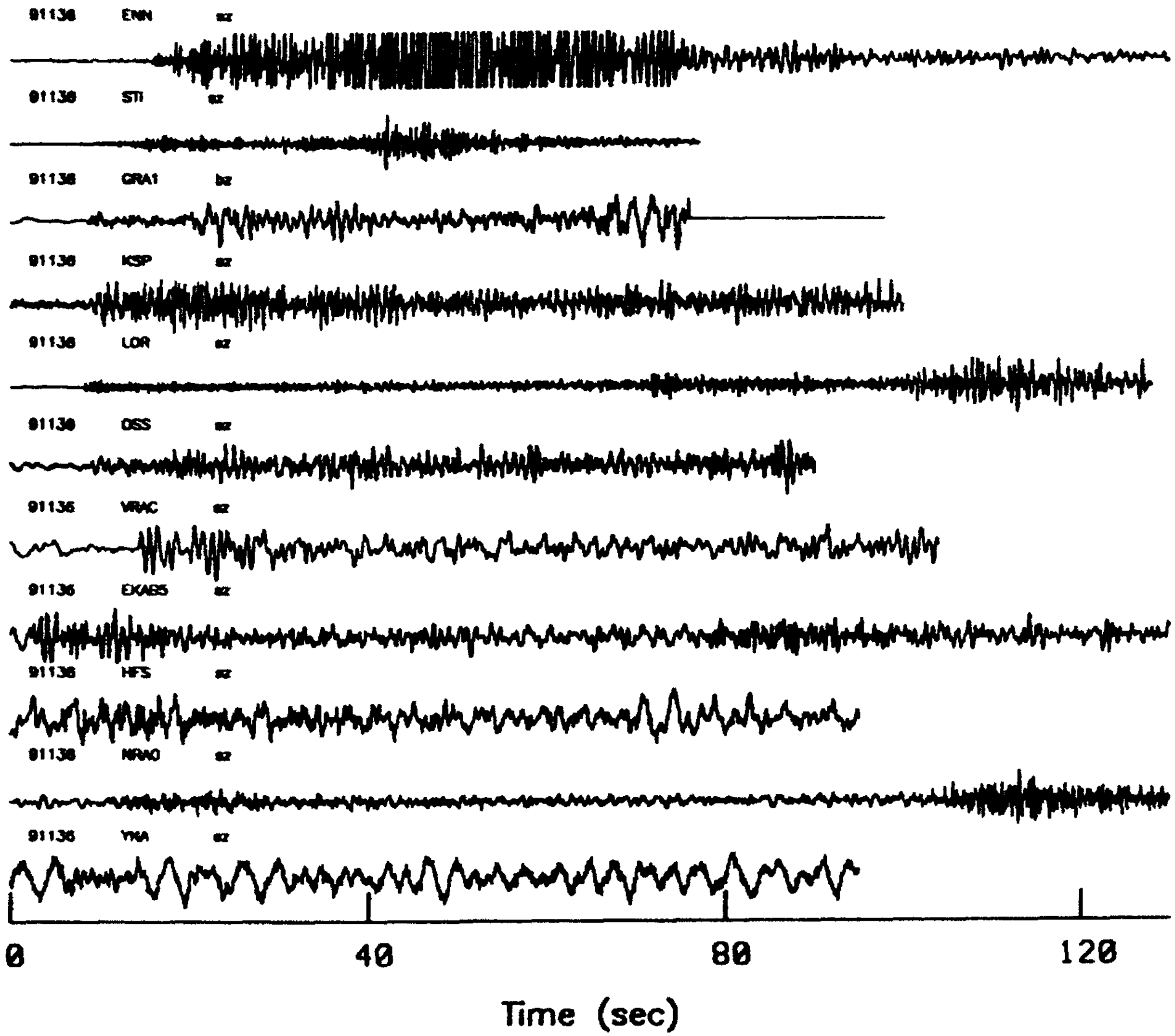

Figure 15. GSETT-2 station records from Ibbenburen, Germany mine tremor of 05/16/91.

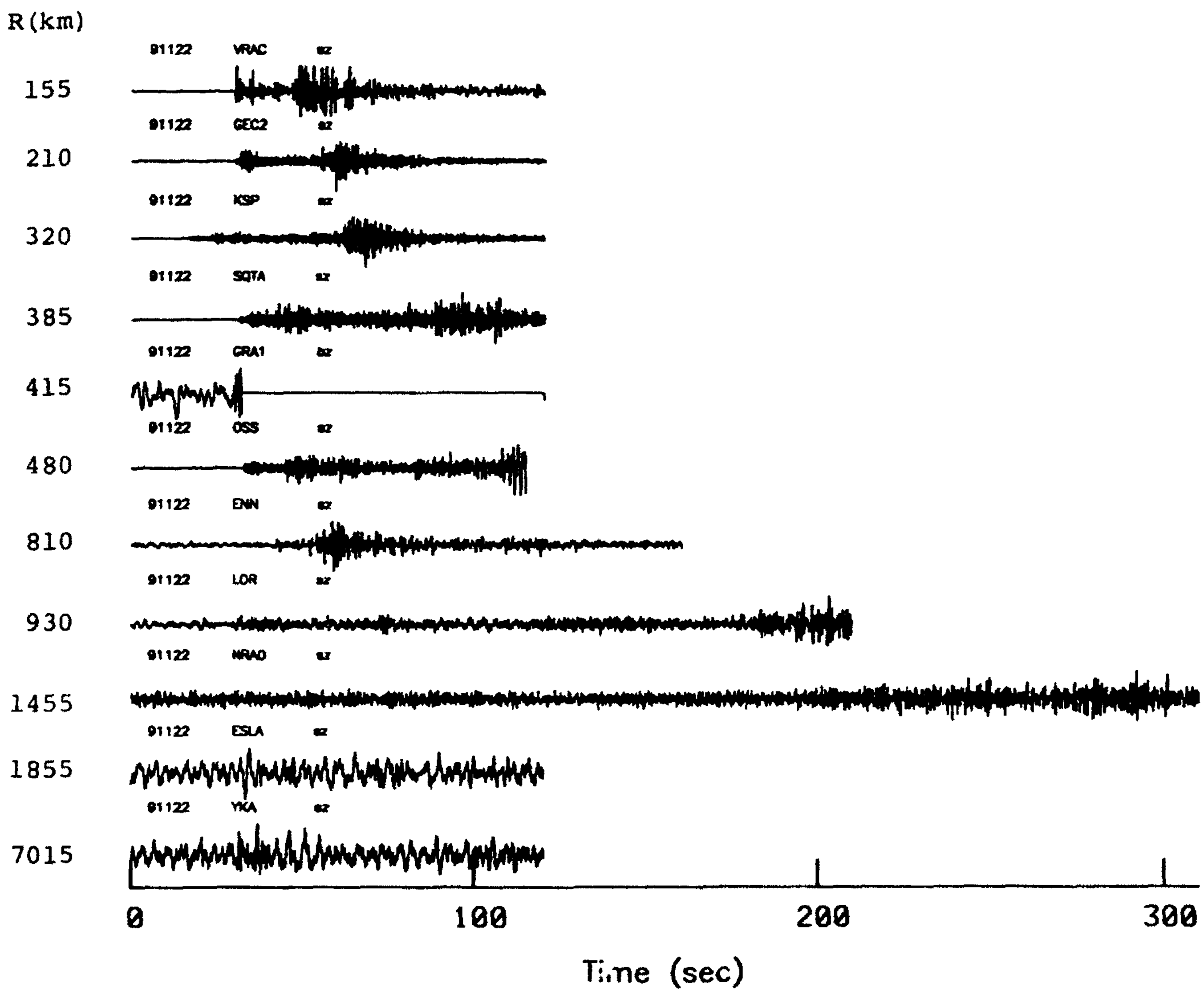

Figure 16. GSETT-2 station records from Austrian earthquake of 05/02/91.

1992 on the German/Belgium/Netherlands border) to supplement the database for the Central European source region.

IV. Discrimination Analyses of Seismic Waveform Data

4.1 Analyses Procedures

In the preceding section of this report, we provided qualitative descriptions and overall views of the seismic databases for events in the rockburst areas of South Africa and Central Europe. In this section we analyze more quantitative measures of the signal behavior. We have focused basically on three types of measurements in these analyses: (1) time-domain measurements of signal amplitudes and their comparison between distinct seismic phases, (2) spectral characteristics of specific seismic phases, and (3) spectral ratios. The latter include ratios of similar seismic phases between events at a single station and also ratios between different phases for the same event.

The relative excitation of different seismic phases determined from time-domain measurements of signal strength is a classical technique for discriminating seismic sources (cf. Bolt, 1976; Douglas, 1981; Blandford, 1982; Office of Technology Assessment, 1988). Examples of such techniques are the M_S versus m_b discriminant used for teleseismic events (cf. Liebermann et al., 1966; Marshall et al., 1966; Marshall and Basham, 1972) and the proposed regional discriminant based on the L_g/P amplitude ratio (cf. Blandford, 1981; Pomeroy et al., 1982). Another time-domain observation which has received some attention over the years is P-wave first motion. We have attempted to evaluate the effectiveness of these and other related time-domain techniques for application to rockburst identification.

In addition to simple amplitude measurements, more robust discrimination techniques frequently use the spectral characteristics of seismic signals. An underground nuclear explosion is generally recognized as a relatively high-frequency source of seismic energy, which in part explains the observed M_S/m_b discriminant cited above. The Variable Frequency Magnitude (VFM) discriminant measure (cf. Archambeau et al., 1974; Evernden, 1977; Savino et al., 1980; Stevens and Day, 1985) provides a quantitative spectral discriminant measure useful for application to teleseismic P waves. For regional events the L_g spectral ratio (cf. Murphy and Bennett, 1982; Bennett and Murphy, 1986) is a discrimination technique which utilizes apparent differences in the frequency content of regional shear waves from underground nuclear explosions and earthquakes. For the rockbursts in this study, we have focussed initially on the basic spectral behavior of the different recorded signals in an effort to discern features which may be distinctive of different source types.

Spectral ratios provide additional refinement and help facilitate comparisons of spectral measurements of seismic phases between events and between different seismic phases for individual events. Bennett et al. (1991, 1992) found that L_g/P spectral ratios obtained at far-regional stations from Eurasian events were frequently diagnostic of differences in source type between underground nuclear explosions and earthquakes. In this study we have used spectral ratios between P phases recorded at a common station to investigate variability between sources from a given region. L_g/P spectral ratios have also been developed for rockbursts and other sources to compare with previous findings to help identify diagnostic spectral differences.

4.2 Time Domain Amplitude Characteristics for South African Events

As pointed out in the preceding section of this report, the regional records obtained at SLR from South African rockbursts and earthquakes typically show strong L_g and clear regional P signals. In an effort to quantify the amplitudes of the L_g relative to P, we measured the signal levels from the time-domain recordings for the group velocity windows appropriate to the L_g and P arrivals as observed at SLR. The L_g window was taken to start at about 3.6 km/sec and the regional P window at about 6.5 km/sec. Although the phases are usually quite clear on the records, we found it useful to use these kinds of window constraints to avoid ambiguous picks. The L_g and regional P amplitudes were measure as the peak motions within the respective time segments following these group velocities. Measurements were made for 41 South African events observed at SLR. All but ten of the events were located in the active mining area within the Witwatersrand basin and are presumed to be rockbursts or mine tremors. The remaining ten events were scattered in southern Africa outside the gold-mining area and are presumed to be natural earthquakes or possibly surface blasts. A few of the events produced clipped records in the L_g window at SLR and only the P signal amplitude level could be measured.

In all cases for the SLR recordings, the L_g signal amplitudes were larger than the P amplitudes. This is shown in Figure 17 for the raw signal amplitude measurements.

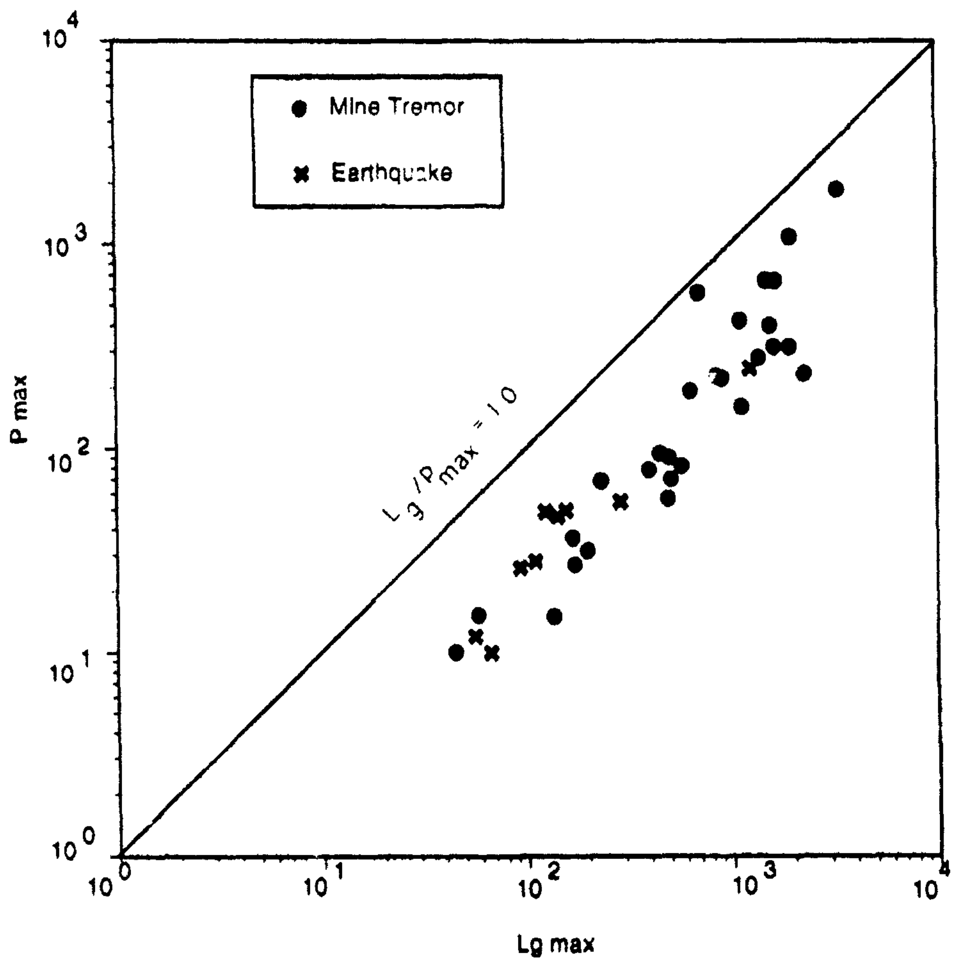

Figure 17. Comparison of L_g and regional P amplitudes observed at station SLR from South African mine tremors and presumed earthquakes.

Both the mine tremors and presumed earthquakes produce L_g/P amplitude ratios significantly greater than 1.0. On average the observed L_g/P amplitude ratio is about 5:1, and there appears to be no strong dependence on the signal strength. The plot also shows the observations from the mine tremors and earthquakes to be intermingled. This result suggests that the mine tremors tend to look like earthquakes with regard to the relative excitation of L_g versus P signals.

One factor not accounted for in the plot of Figure 17 is differences in epicentral distance between events. In particular, as described in the preceding section, the distance to station SLR from individual mining areas varies; and the distance to the gold mines from SLR is generally less than that to the earthquake epicenters in the database. One way to account for this effect is to apply an attenuation correction, similar to that used by Blandford (1981), to normalize the amplitudes to a common distance range. The assumed attenuation relationship used here is of the form $1/R^{2.5}$ for P_{max} and $1/R^2$ for L_g. This is essentially the same relation used by Blandford for the eastern United States, a region with relatively stable crustal tectonics similar to South Africa. The P_{max} attenuation assumed is somewhat more severe than that derived by Der et al. (1982) for P_n and P_g phases in southern Africa. However, comparing the $1/R^{2.5}$ attenuation assumed here and the $1/R^2$ found by Der et al., there would be little significant difference in the fit to the observations over the relevant distance range from 1° to 10°. We applied the attenuation correction to normalize all observations to a distance of 1000 km. These normalized measurements are plotted in Figure 18. The correction makes little difference in the overall appearance of the data except to spread the values over a somewhat larger range of L_g amplitudes. The earthquake observations appear to be interspersed throughout the mine tremor results. The scatter in the observations about some mean relation is roughly a factor of two to three. The L_g/P_{max} ratios in all cases are significantly greater than 1.0, unlike the behavior seen for underground nuclear explosion tests in other parts of the world.

To some extent the scatter in the observations could be related to mechanism variations between events or changes in the location of the observing station relative to the radiation pattern of the source. Unlike simple explosions which should have a uniform seismic radiation pattern at all azimuths, we expect seismic signals from earthquakes to vary with azimuth. Most models for rockbursts are also expected to produce non-uniform seismic radiation, but some other models may be nearly isotropic. In order to get a better idea of possible effects of mechanism variation between events,

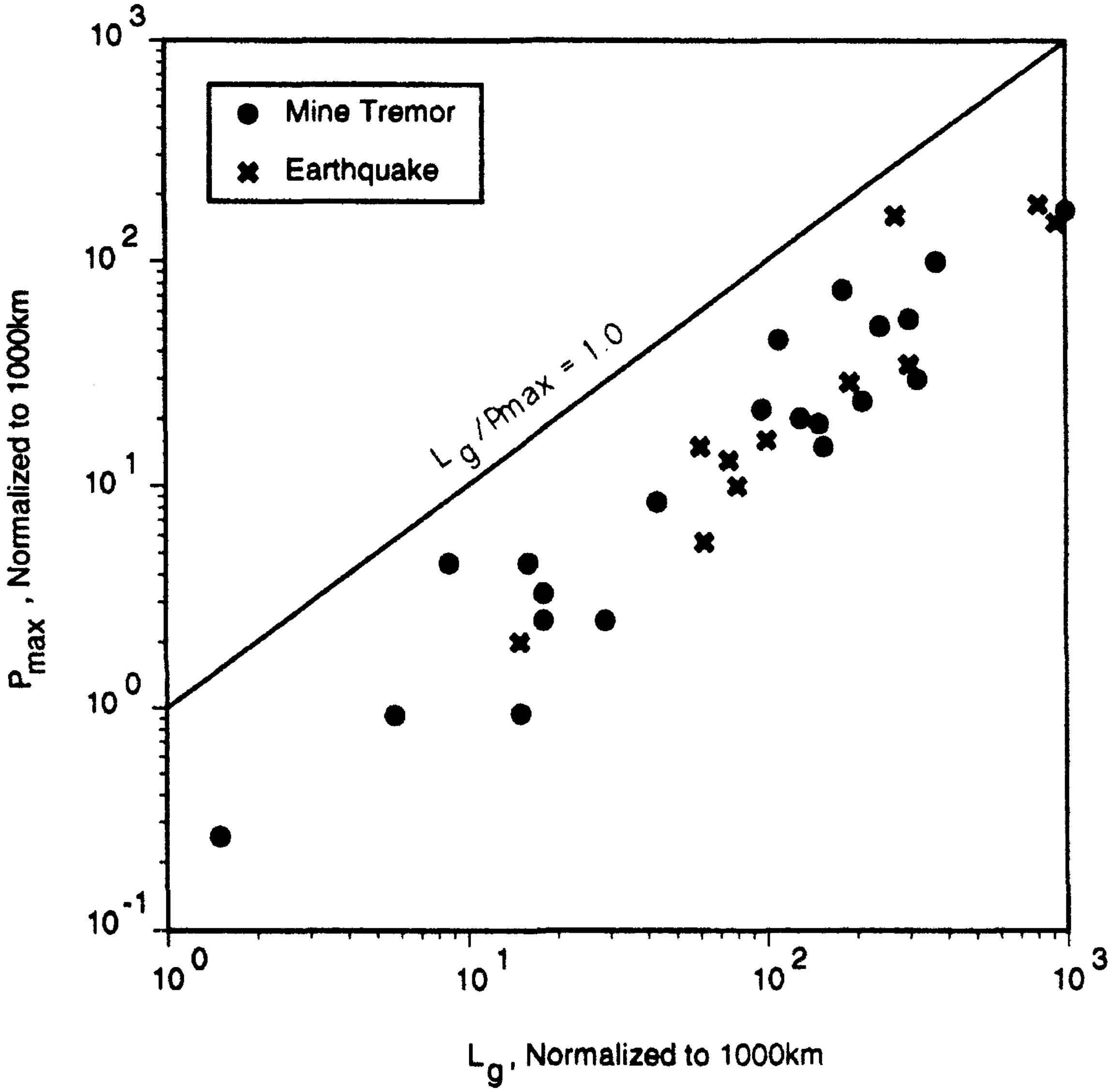

Figure 18. Distance normalized P versus L_g amplitudes measured at station SLR for South African mine tremors and presumed earthquakes.

we have analyzed the initial P motions recorded at SLR for several South African rockburst events.

In most cases the initial P signals appear remarkably consistent for events from specific mining areas. For example, Figure 19 shows segments of the vertical-component P-wave windows from two events from the East Rand ($R \cong 55$km) area and three events from the Klerksdorp area ($R \cong 195$km). The P-wave signals are nearly identical for events from a given mine, matching closely in waveform detail. Interestingly, however, the first motions are quite different for events in the two source areas. The first motions at SLR for the East Rand events are sharply compressional, while the Klerksdorp event first motions are more emergent and dilatational. As already noted, this observation is probably strongly affected by the distances to the station. One interpretation of the signal differences would be that the mechanisms from the two mines are similar but the initial signals from the East Rand events are direct P waves leaving the source nearly horizontally while the first signals from the Klerksdorp sources are P_n phase leaving the source downward. From this we would infer that the initial phases are sampling different portions of the focal sphere from a non-symmetric source. In fact, there appears to be clear evidence in the P signals from the Klerksdorp events of a strong second arrival, like the first arrival from East Rand, which could be the crustal P phase. Following this interpretation we would conclude that the mechanisms for these South African rockbursts are not isotropic.

Perhaps a more interesting observation is the comparison shown in Figure 20 for several mine tremors from the Far West Rand mining area recorded at SLR. In this case we see some notable differences in the initial P motions between events. The first motions for the top three events appear to be clearly dilatational while the bottom two are compressional. Since the events are at a common range and azimuth, the most likely explanation for the differences would seem to be a change in mechanism. There also appear to be significant differences in later portions of the P-wave windows which could also be attributed to mechanism variation. Data from a more complete network of stations surrounding some of these rockburst sources, as well as other components of motion, would be useful for a refined interpretation of the rockburst mechanisms.

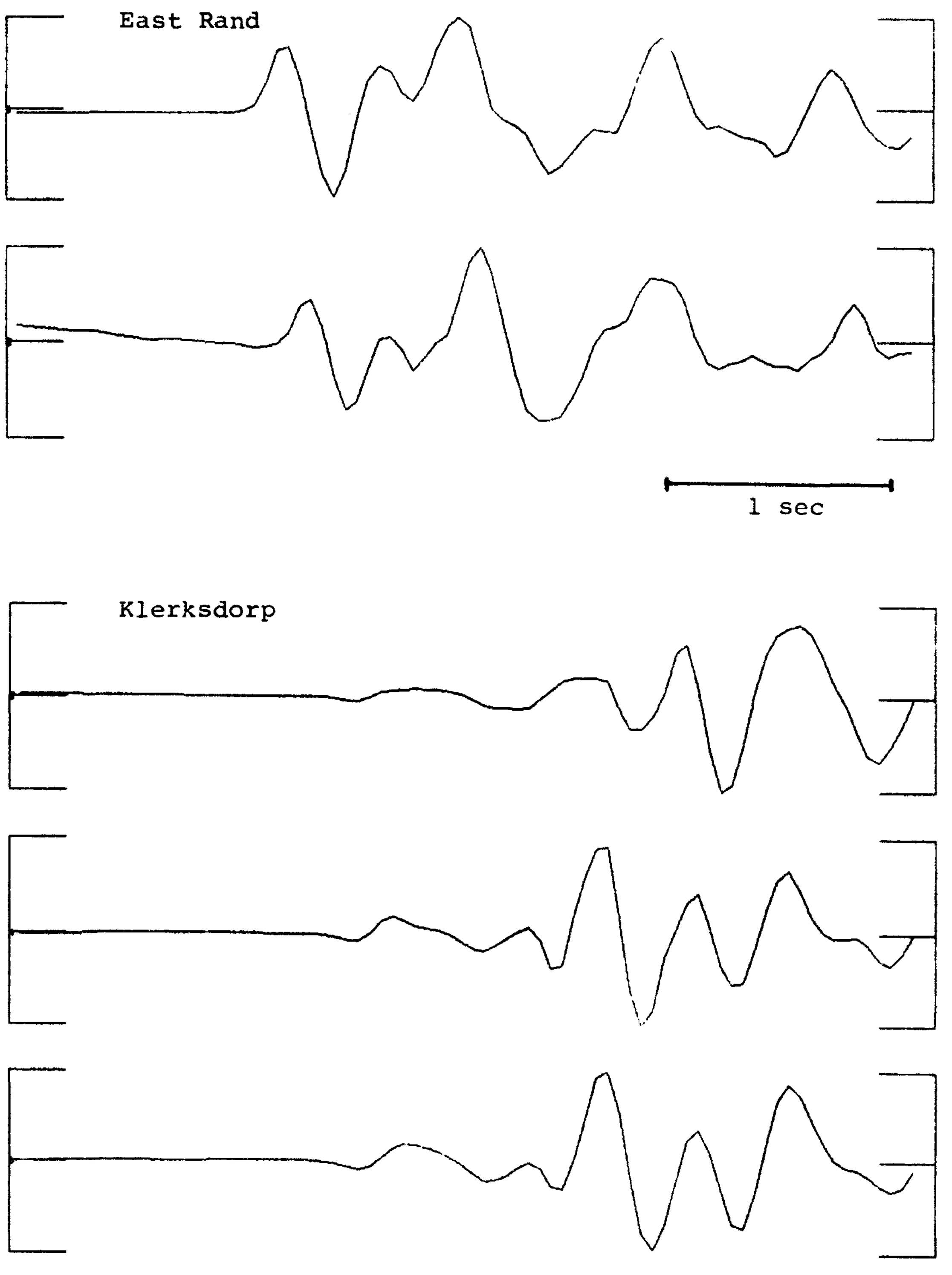

Figure 19. Initial P waveforms at SLR for mine tremors from the East Rand and Klerksdorp mining districts.

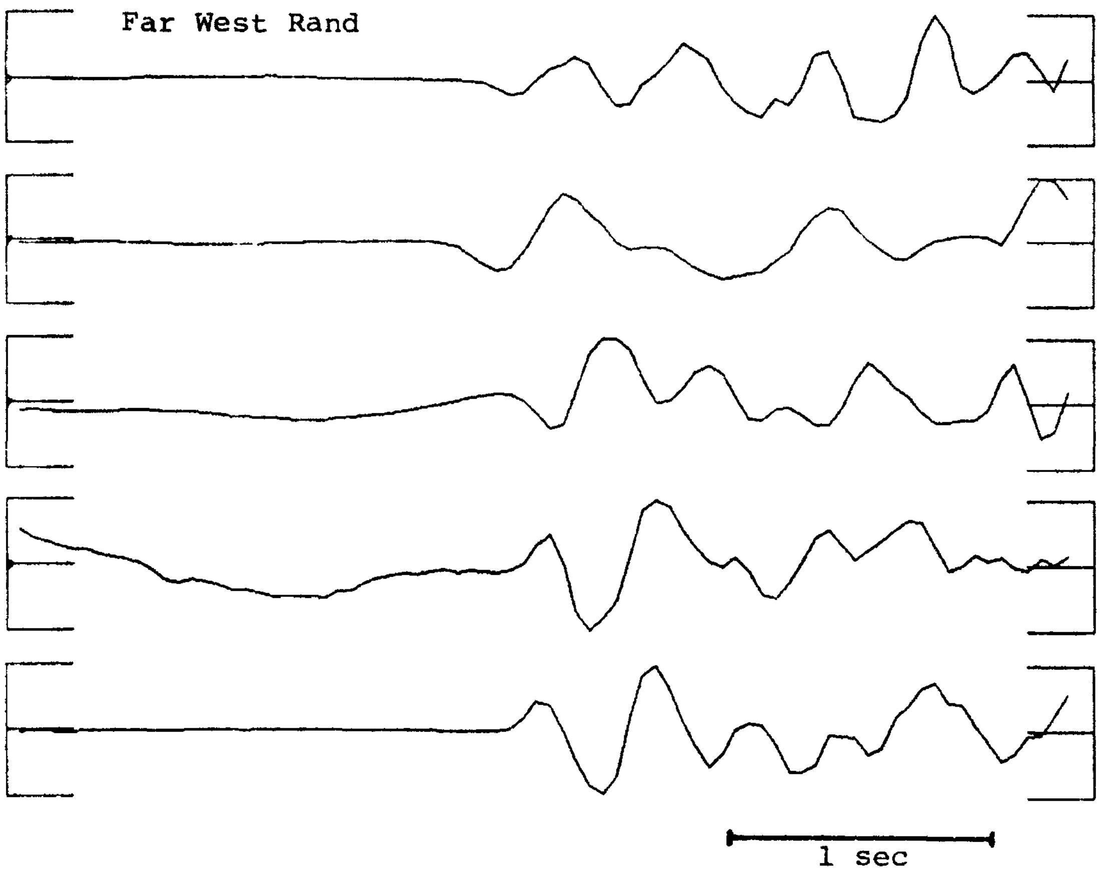

Figure 20. Initial P waveforms at SLR for mine tremors from the Far West Rand mining district.

4.3 Spectral Characteristics for South African Events

In addition, to the time-domain character of seismic signals from South African rockburst, spectral analyses provide important tools for use in discrimination. Our analyses to date have concentrated on obtaining some preliminary indications of spectral behavior and variability between events.

Figures 21 through 23 show L_g spectra for four rockbursts and two regional earthquakes recorded at SLR. The spectra were computed for a window including a group velocity range from about 3.6 km/sec to 3.1 km/sec. Noise spectra, which are not shown here, were also computed from pre-P waveform segments. The L_g signal levels in all these cases are strong, so that signal-to-noise (S/N) ratios are high over the entire frequency band of interest from about 0.5 to 10 Hz. In fact, for these events which have magnitudes in the range 3.0 to 3.5 M_L, the S/N ratio averages about a factor of ten over this band. An important factor in the strong signal levels is the station range which is less than 500 km in all cases. At larger ranges we would expect significant deterioration in the S/N levels particularly at higher frequencies.

Figure 21 shows the L_g spectra for two rockburst events in the Klerksdorp area at a range of about 195 km from SLR. The two events, which occurred just over one day apart (06/27/82 and 06/28/82), had magnitudes of 3.6 and 3.4 M_L. Although there appear to be some minor differences, the L_g spectra are generally quite similar. Both spectra peak near 2 Hz and the decay rates above the peak are about the same in both cases.

In Figure 22 are shown the L_g spectra for two rockburst events in the Orange Free State mining district. The range to SLR in this case is somewhat greater at about 285 km. These two events had magnitudes of 3.6 and 3.2 M_L. The spectra again have quite similar shapes featuring double peaks, at 1 and 2 Hz, followed by a steady decline at higher frequencies. The difference in magnitude accounts for most of the difference in spectral level at low frequencies observed between the two events. However, the larger event (viz 11/19/81) appears to have a somewhat more rapid spectral decay rate than the smaller event (viz 05/24/83) suggesting a possible source difference. The events have similar but not identical locations; so attenuation differences seem unlikely but source site response could be a factor. If the observation represents a true source effect, it seems to indicate that the two events produced comparable seismic excitation at

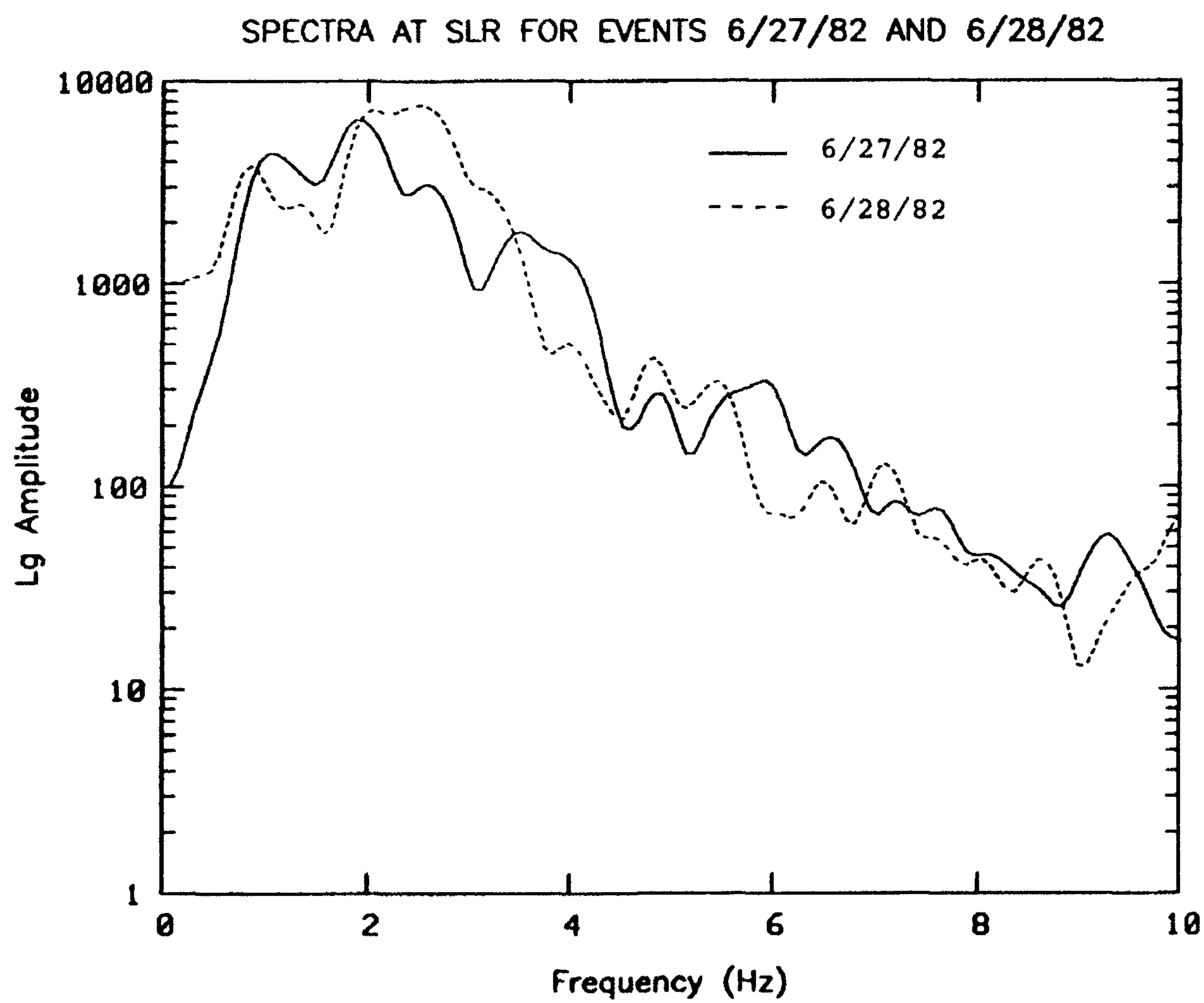

Figure 21. Fourier spectra of L_g signals at station SLR from two mine tremors in the Klerksdorp area.

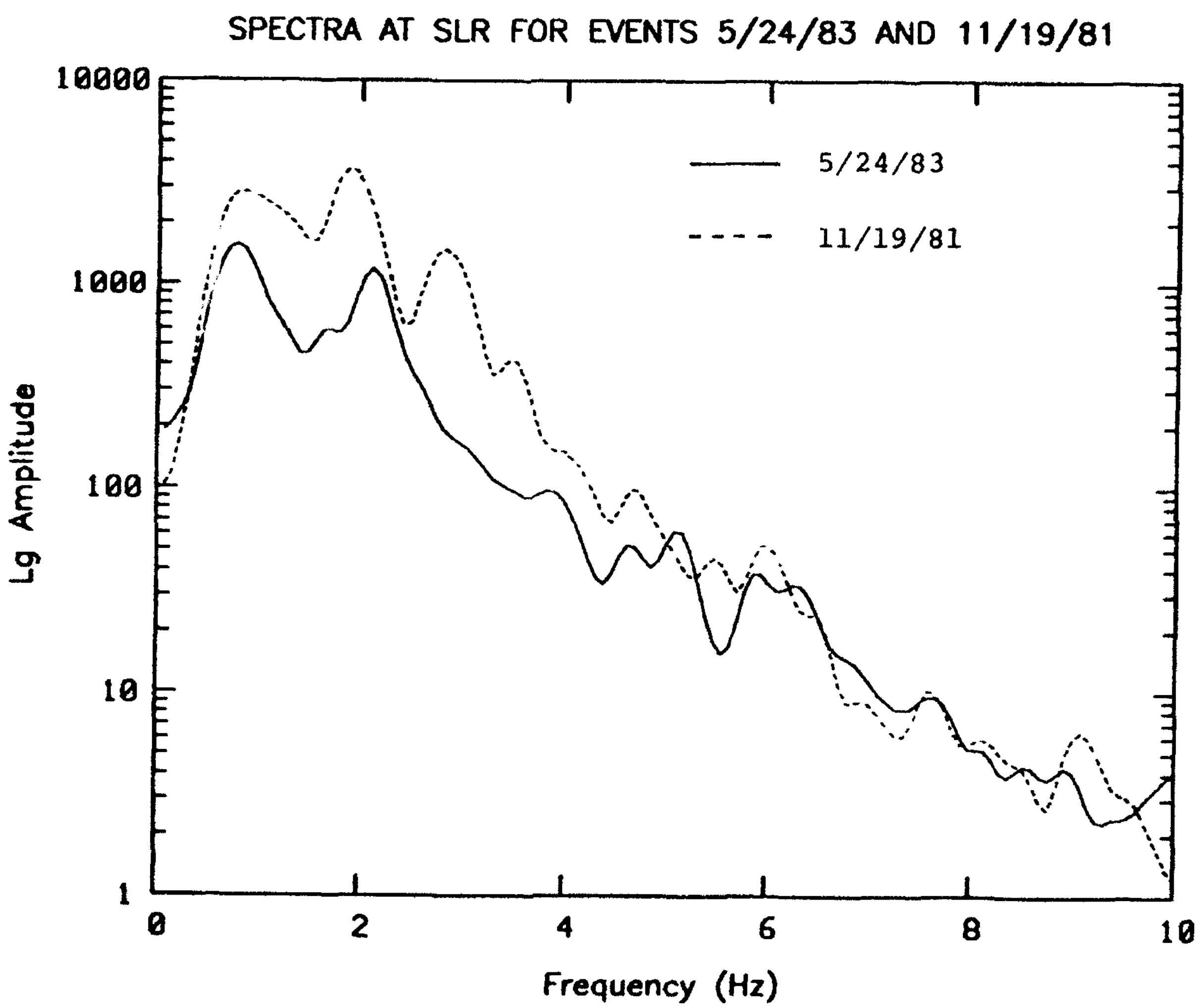

Figure 22. Fourier spectra of Lg signals at station SLR from two mine tremors in the Orange Free State area.

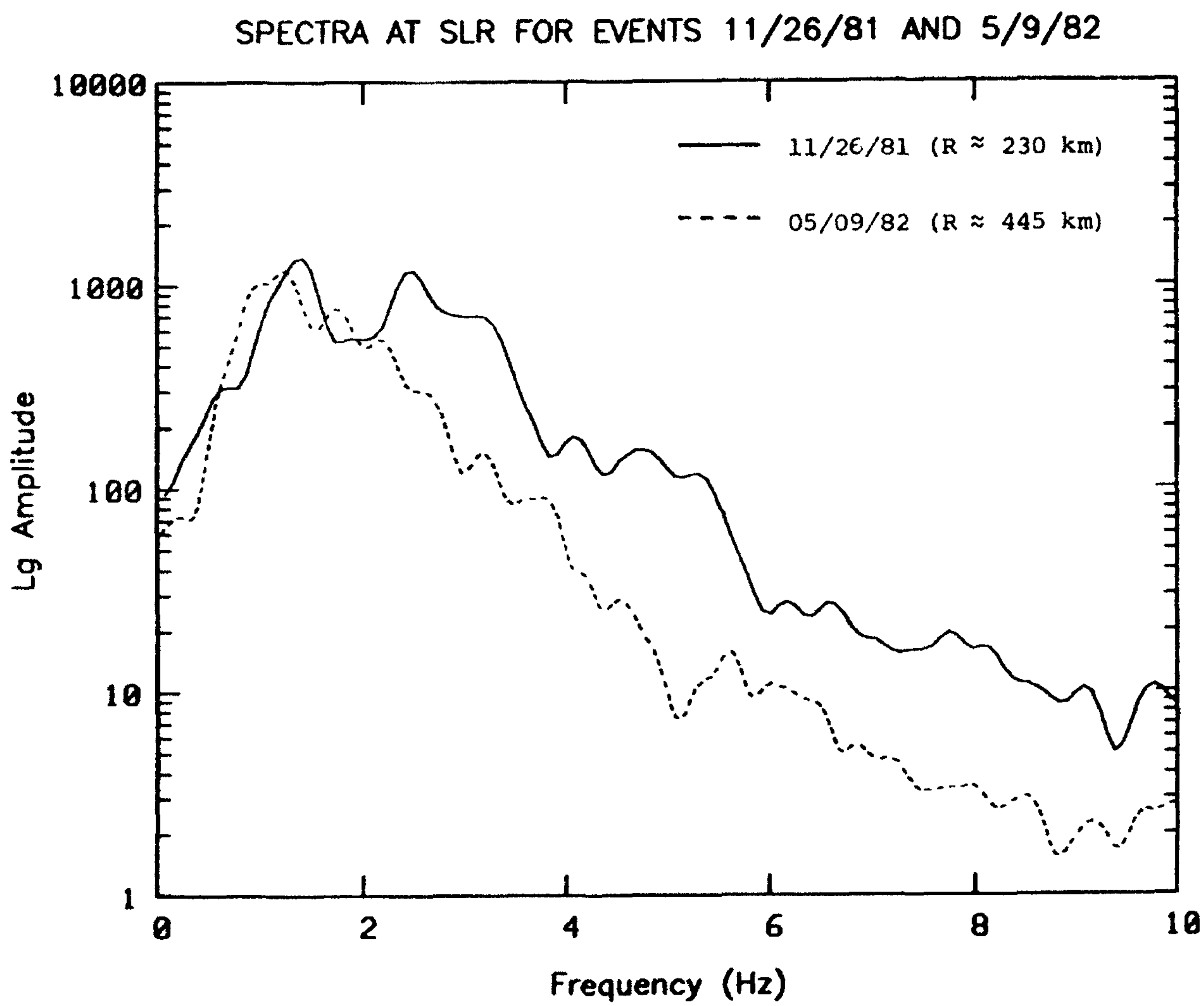

Figure 23. Fourier spectra of L_g signals at station SLR from two regional earthquakes.

higher frequencies; but the larger magnitude event may have been more efficient at frequencies near 1 Hz. However, this case is not strong and needs to be corroborated by additional events covering a wider range of magnitudes.

For comparison purposes we show in Figure 23 the L_g spectra for two presumed earthquakes recorded at SLR. The range of these events in one case (viz 11/26/81) is about 230 km and in the other (viz 05/09/82) about 445 km. The events had magnitudes of 3.2 and 3.4 M_L. respectively. The two earthquakes show similar L_g spectral peaks just above 1 Hz. However, above 2 Hz the two spectra digress. This difference in spectral decay seems most likely to be attributable to attenuation differences due to the larger distance. Observations of this type could be useful for quantifying L_g attenuation as a function of frequency for South Africa. If we focus on the L_g spectrum for the 11/26/81 presumed earthquake, which has a range more nearly comparable to those of the rockburst events, we see that the spectral shape is quite similar to those of the L_g signals from rockbursts in the Klerksdorp area recorded at SLR. The spectra all peak in the 1 to 3 Hz range and show similar decay at higher frequencies. The comparison isn't quite as good for the 11/26/81 presumed earthquake and the Orange Free State rockbursts. The comparisons show differences in both location of the spectral peaks and in the spectral decay. The latter could be attributed to increased attenuation because of the somewhat larger distance. We intend to make additional comparisons of this type to get a better idea of the relative influences of attenuation and source factors on the L_g spectral observations.

At some of the more distant stations, we have also been looking at P-wave spectral characteristics from many of the larger South African rockbursts. Figure 24 shows the P-wave spectra at stations BCAO ($R \cong 32^{\circ}$) and ZOBO ($R \cong 87^{\circ}$) for two rockbursts with magnitudes near 5 m_b. These events occurred on 06/12/80 and 08/11/86 and had magnitudes of 4.8 and 4.9 m_b, respectively. The spectra in all cases are for a 6.4-second window starting just prior to the P arrival on the vertical-component short-period records. To help identify the useful frequency band at these distant stations, a similar Fourier spectrum was computed for a noise segment preceding the P arrival. In each case this noise spectrum is superimposed on the P-wave spectral plots.

At BCAO the signal-to-noise level appears to be above 1.0 up to about 6 Hz for the 06/12/80 rockburst but only up to 4 Hz for the 08/11/86 event. At ZOBO the signal-to-noise ratio is above 1.0 up to about 4 Hz for the 06/12/80 rockburst but

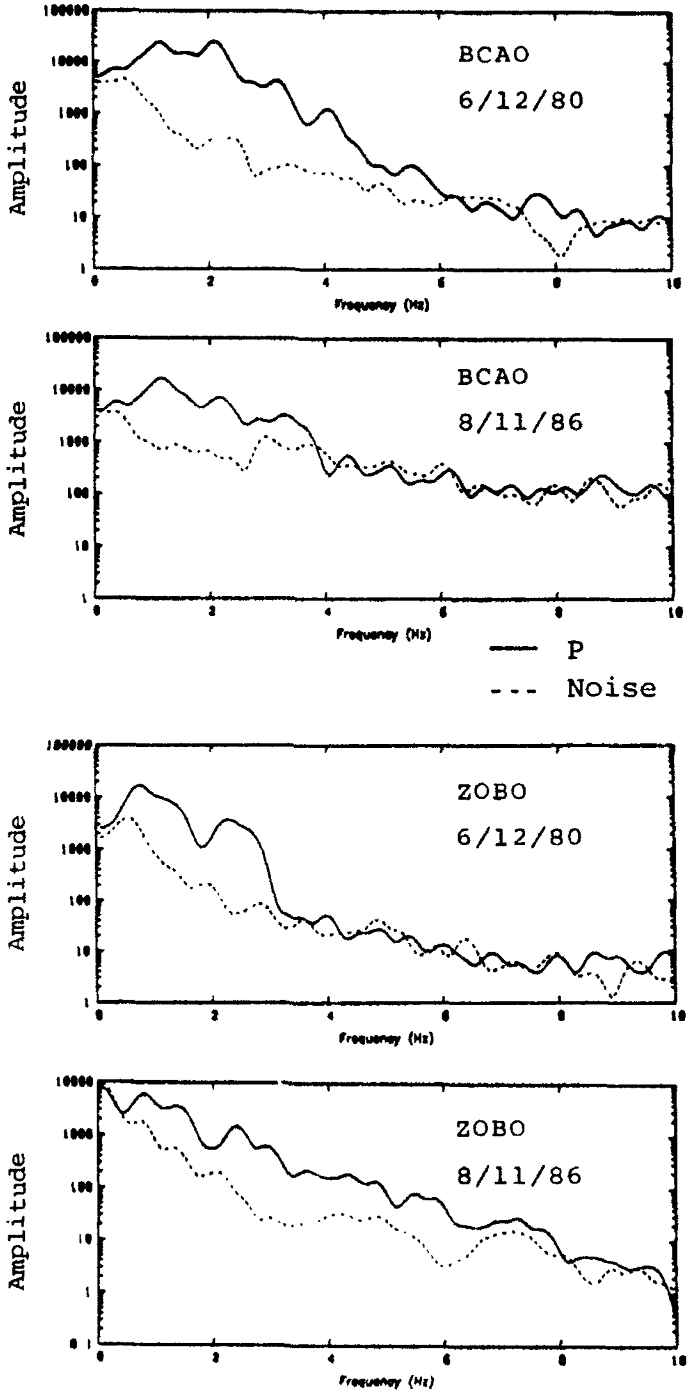

Figure 24. Fourier spectra for P signals at stations BCAO and ZOBO for two large South African rockbursts.

surprisingly appears to be above 1.0 to frequencies near 8 Hz for the 08/11/86 rockburst. Concentrating first on the BCAO spectra, the P-wave spectral shapes and levels for the two events are quite similar over the band of useful frequencies (i.e. up to 4 Hz). The main reason for the cutoff at 4 Hz for the 08/11/86 event appears to be related to the higher level of background noise at high frequencies on that date. The biggest difference within the 0 to 4 Hz band occurs near 2 Hz where there may have been some type of relative enhancement for the 06/12/80 rockbursts. The reason for the cutoff near 4 Hz for the 06/12/80 event at ZOBO is unknown. The noise levels on the two dates are about the same over the entire frequency band, so the P-wave spectrum for the 06/12/80 event appears to be depleted in energy at frequencies above 3 Hz relative to the 08/11/86 event at ZOBO. However, we did not see this behavior at BCAO for the same two events. One explanation might be dependence of the source spectrum on azimuth or take-off angle, but clearly additional observations are required to support such a conclusion. One way of isolating these kinds of spectral differences between events is by comparing spectral ratios, as will be described more fully in the following section.

4.4 Spectral Ratios for South African Events

As noted in the introduction to this section, spectral analyses can provide a powerful tool for identifying differences in seismic signals between events with different source types. In Section 4.2 above we found that time-domain L_g/P amplitude ratios for South African rockbursts recorded at station SLR were normally greater than 1.0 and intermingled with similar measurements from presumed earthquakes in the region. We have also been looking at the dependence of this measurement on frequency using L_g/P spectral ratios determined from the SLR recordings. In addition, we have been evaluating the use of P-wave spectral ratios between different South African rockbursts recorded at a common station to investigate signal variability which may be dependent on source changes. We describe here the preliminary results of these observations.

We begin with a discussion of three events recorded at SLR which were described in the preceding section. Figures 25 and 26 show L_g/P spectral ratios determined from the SLR signals for two South African rockbursts and an earthquake with similar magnitudes (viz 3.6, 3.6 and 3.2 M_L) and comparable ranges (viz 195, 285 and 230

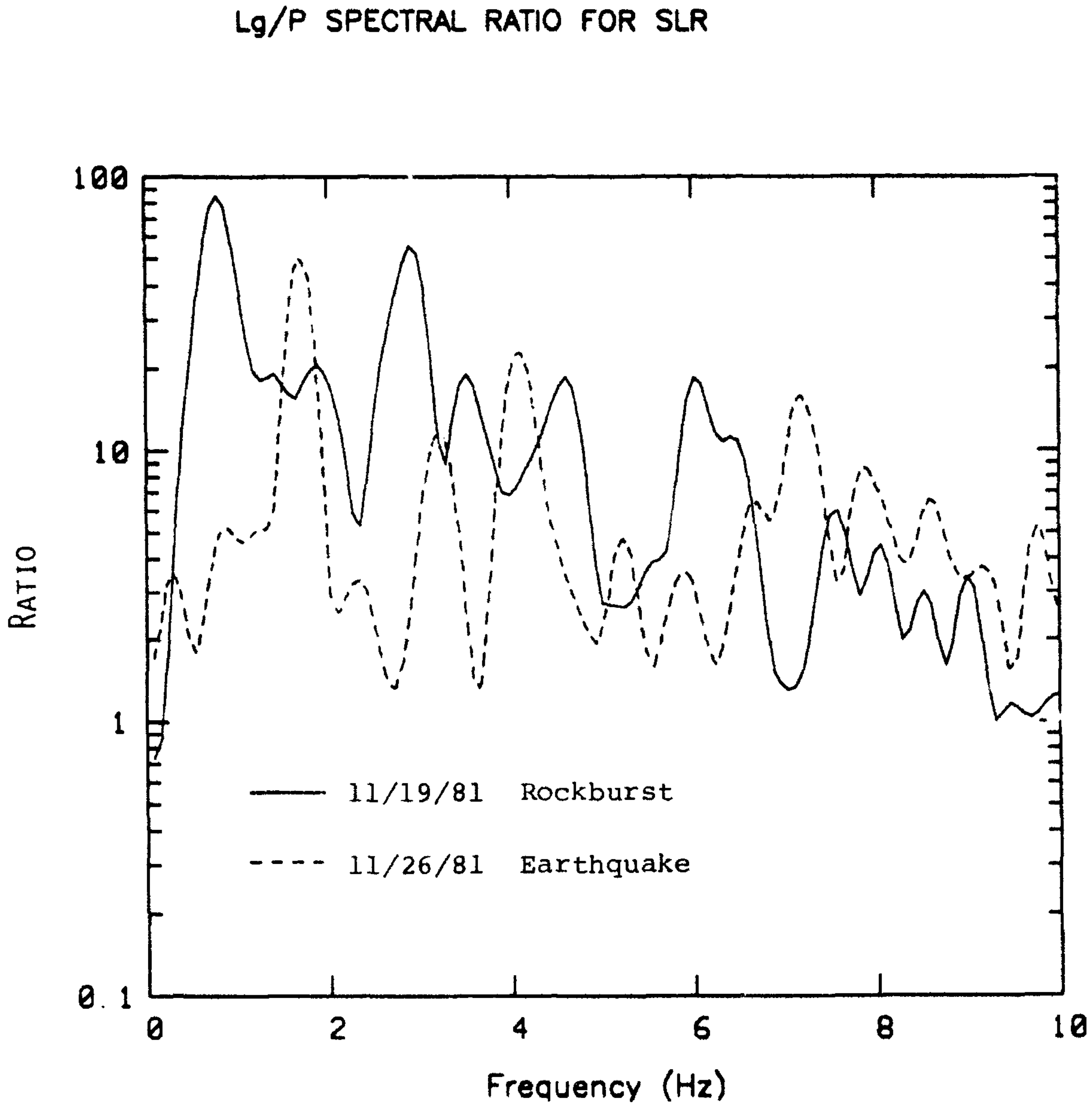

Figure 25. Comparison of Lg/P spectral ratios at station SLR for Orange Free State rockburst and regional earthquake.

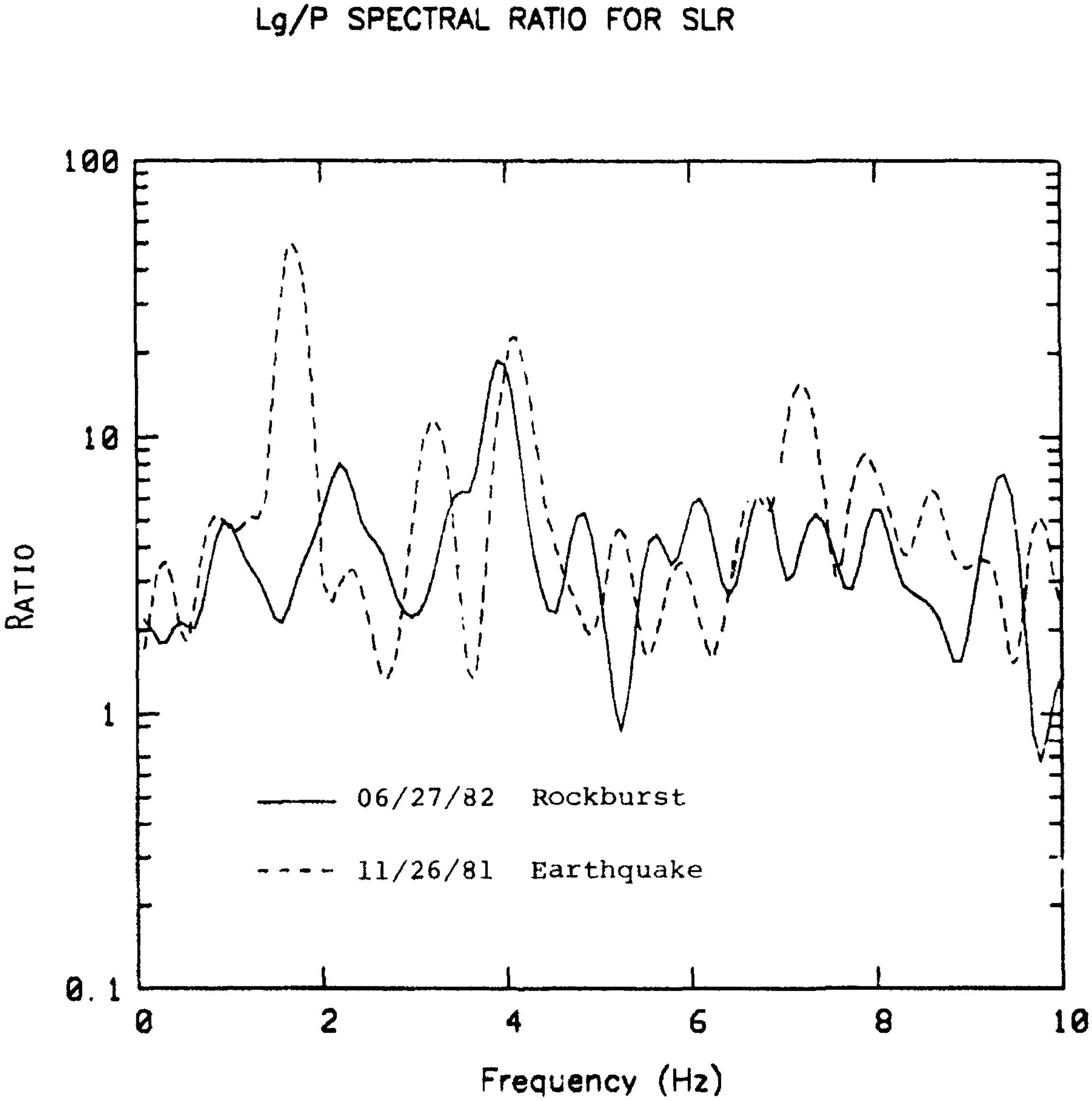

Figure 26. Comparison of L_g/P spectral ratios at station SLR for Klerksdorp rockburst and regional earthquake.

km). The respective events are a rockburst in the Klerksdorp area (06/27/82), a rockburst in the Orange Free State area (11/19/81) and a presumed regional earthquake (11/26/81). Figure 25 shows the comparison of the L_g/P ratio for the Orange Free State rockburst and the earthquake. In both cases the L_g/P ratios are well above 1.0 across the entire frequency band from 0 to 10 Hz. For the rockburst the L_g/P ratio has its maximum value of almost 100 near 1 Hz. Although the ratio is rather oscillatory, there appears to be an overall steady decline to a level near 1.0 at 10 Hz. Other Orange Free State rockbursts, although not presented here, showed similar behavior. The earthquake L_g/P spectral ratio also shows a great deal of fluctuation with frequency but appears to be generally lower than the rockburst ratios. The maximum value occurs near 2 Hz, and the ratio does not show the decline with frequency seen in the rockburst observation.

In Figure 26 we show the comparison between the L_g/P spectral ratios for the Klerksdorp rockburst and the regional earthquake. Except for the large spike in the earthquake ratio just below 2 Hz, the rockburst and earthquake spectral ratios are quite similar. Both spectra are well above 1.0 across the frequency band, oscillating about a value near 5.0. Therefore, the observations indicate generally similar spectral ratios for Klerksdorp rockbursts and presumed regional earthquakes recorded at SLR. However, it should be noted that relatively large fluctuations in the L_g/P ratio could cause differences if the measurements are restricted to narrow frequency bands. We are continuing to explore the regional phase spectral measurements from South African events to determine what features of the spectra might be diagnostic of source differences.

With regard to the more distant stations from the South African events, our focus has been on investigating variability in the spectral content of the P phases recorded at a few select stations. P-wave spectral ratios between different rockburst events measured at common stations eliminate the propagation path factors permitting more direct consideration of source variations. Figure 27 shows the ratio of the P-wave spectrum of the 11/12/82 rockburst to the 06/12/80 rockburst measured at station BCAO. Both events were in the Klerksdorp mining region. We showed above that the P-wave spectrum for the 06/12/80 rockburst had signal well above noise over a broad frequency band up to about 8 Hz, so it should provide a good base against which to compare other events. The 11/12/82 rockburst occurred very close to the 06/12/80 event, so we believe the P-wave spectral ratio should represent differences in the P-

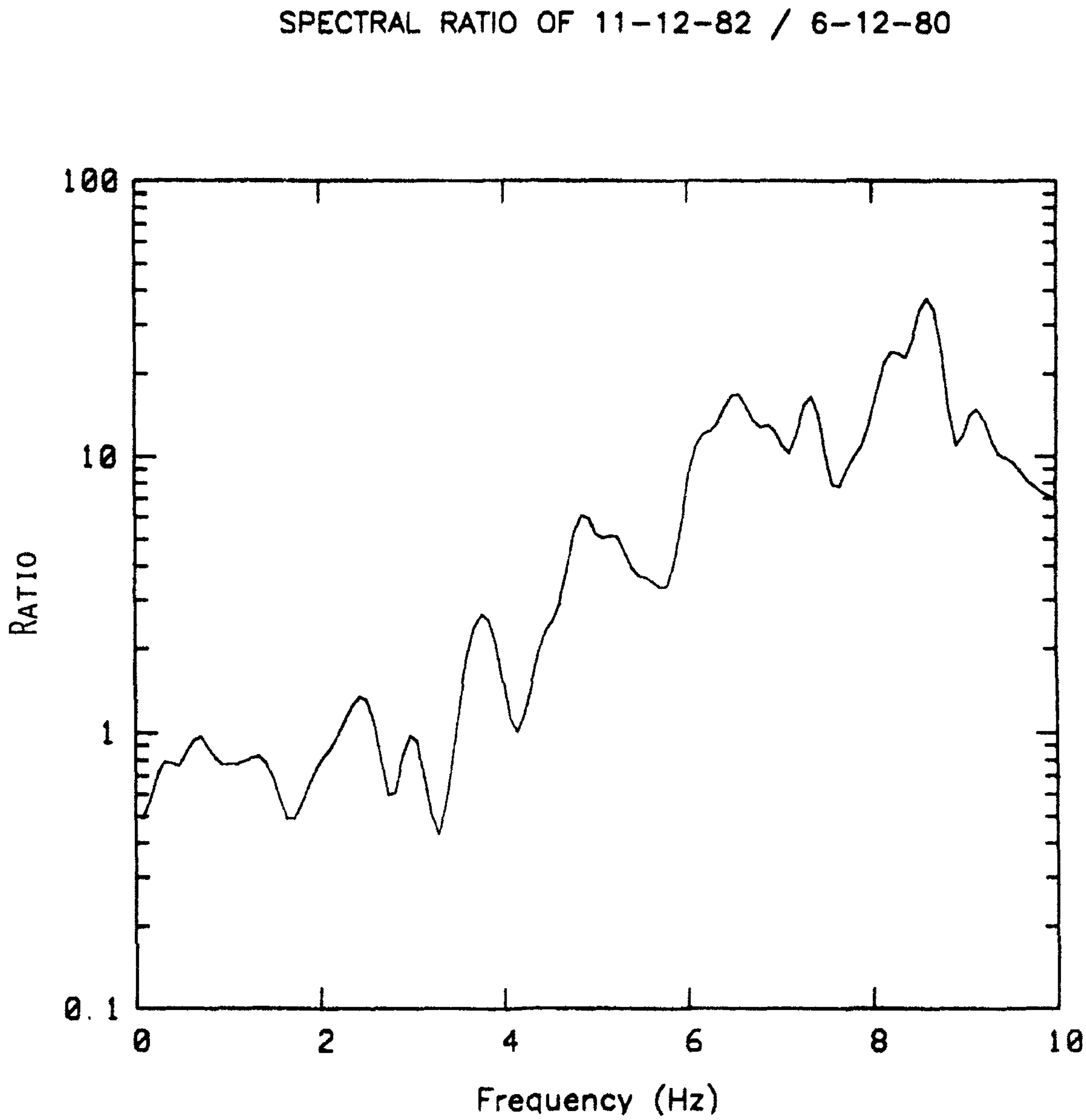

Figure 27. Spectral ratio of P-wave signals at BCAO for two large South African rockbursts from the Klerksdorp area.

wave seismic source as a function of frequency. Focusing first at low frequencies, Figure 27 shows the ratio varying about a level near 0.8 in the frequency range 0 to 3 Hz. This appears to be counter to network magnitude estimates which indicate that the 11/12/82 event was 0.2 magnitude units larger. Over the band from 2 to 8 Hz, the spectral ratio in Figure 27 shows a rapid increase; but much of this may not be real. At higher frequencies, above about 5 Hz, the P-wave spectrum for the 11/12/82 rockburst appears to be contaminated by background noise; so its level at high frequencies is artificially inflated. However, we also see an increase in the ratio within the 2 to 5 Hz band which appears to be real. Thus, the spectral ratio appears to indicate some possible differences in the P-wave source between these two nearby rockbursts. This conclusion appears to be corroborated by the P-wave spectral ratio for the same two events at station ZOBO which is shown in Figure 28. In this case the individual spectra are again contaminated by noise above 4 Hz, so we confine our analysis to lower frequencies. In the 0 to 3 Hz range we see the P-wave spectral ratio varying about a level near 0.6 to 0.7. This level is slightly lower than that seen at BCAO and is again opposite to what we would expect considering the larger magnitude of the 11/12/82 event. Over the interval 2.5 to 4 Hz, the spectral ratio has a rapid increase similar to that seen at BCAO.

Figure 29 shows two additional examples of P-wave spectral ratios at station BCAO from South African rockbursts. These events were in the Orange Free State (02/17/80) and Far West Rand (09/15/86), so they were somewhat farther removed from the reference event. The P-wave spectral ratios again show similar behavior to that described above. At low frequencies the spectral ratio levels are less than 1.0, averaging 0.3-0.4 and 0.4-0.5, respectively. Again the ratio in this band seems low considering all events have comparable magnitudes (within 0.2 units). Since the sources in this case are somewhat separated from the base event, source site response differences could contribute to the observed difference in the ratio. At frequencies above 2 Hz the P-wave ratio increases; but it is unknown to what extent this represents source differences or noise contamination for these two events.

The preliminary indications from these analyses with regard to the feasibility of using the teleseismic P spectra for distinguishing rockburst events are mixed. The fact that we are able to see a fairly broad frequency band of the teleseismic P at individual stations, which may not be the highest quality, even at very large distances is viewed as positive. It also seems promising that we appear to be seeing some differences in the

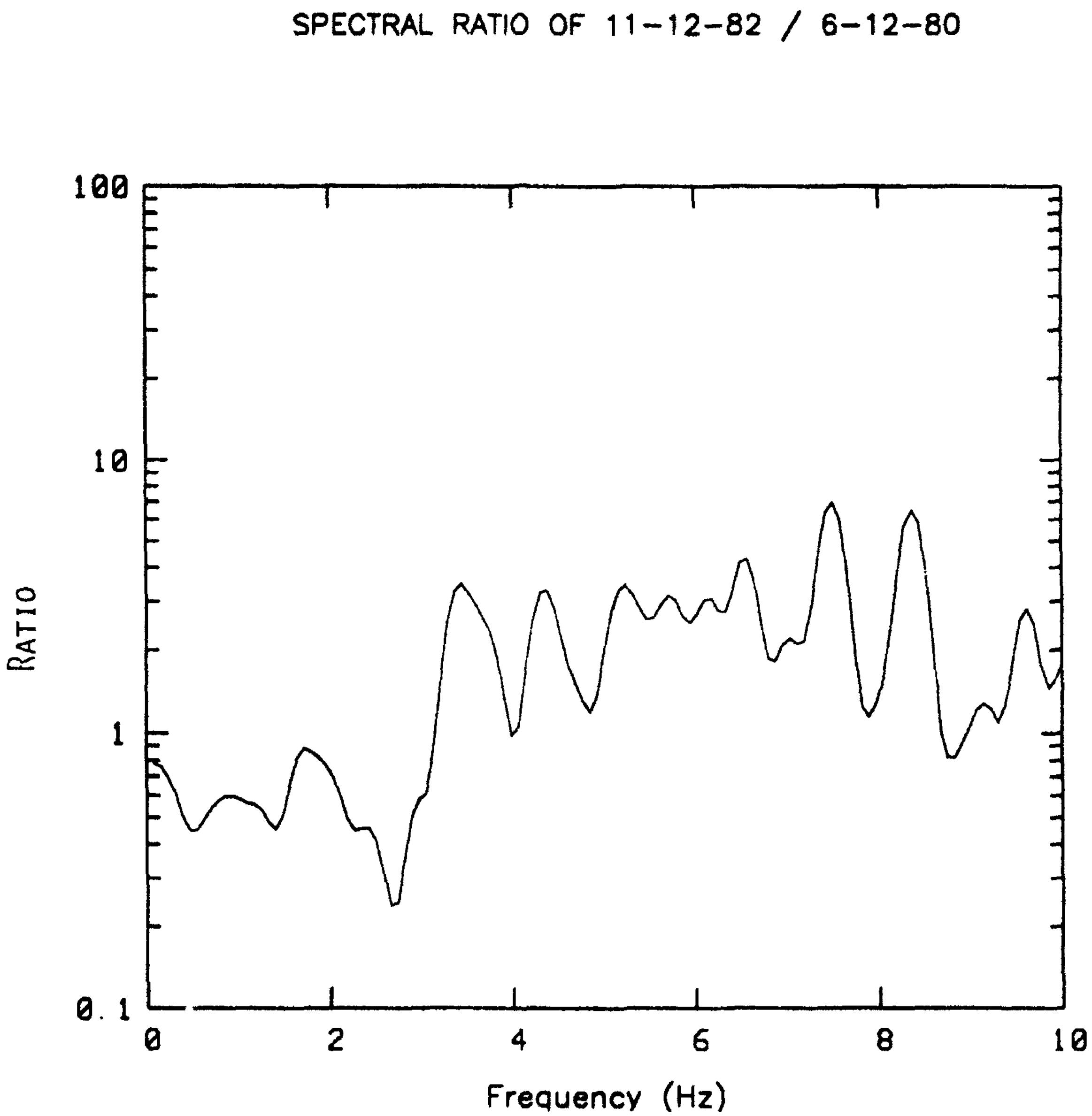

Figure 28. Spectral ratio of P-wave signals at ZOBO for two large South African rockbursts from the Klerksdorp area.

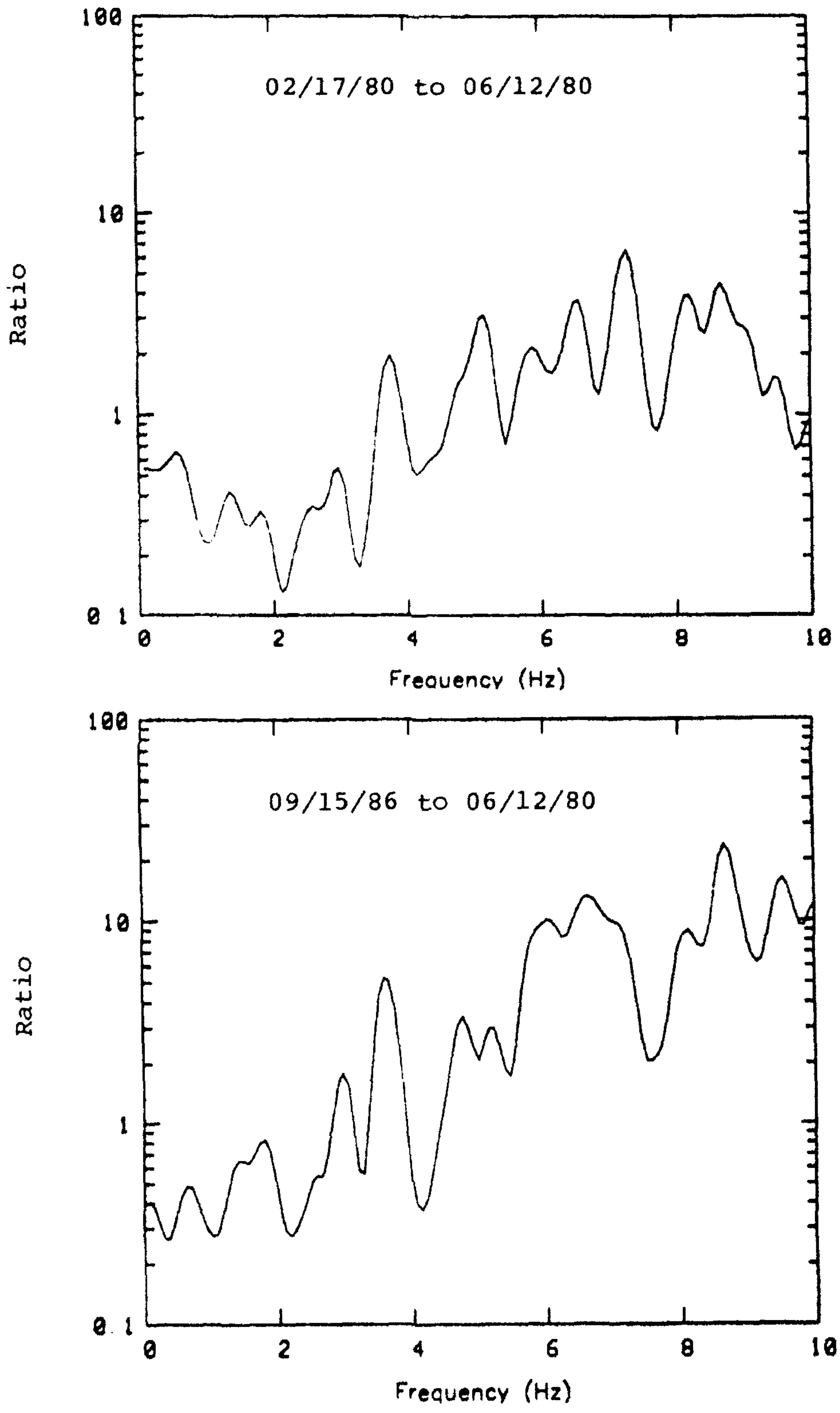

Figure 29. P-wave spectral ratios at BCAO for two additional large South African rockbursts.

spectra which may be related to source variations. On the less favorable side is the fact that most of the events for which we have been able to see teleseismic P have large magnitudes while the majority of rockbursts in mining areas throughout the world are small. So teleseismic techniques may not be useful for identifying most rockbursts. We were also somewhat disappointed by the apparent rapid fluctuations in the P-wave spectral ratios with frequency which would appear to indicate a rather complex source. On the other hand, if such source complexity is confirmed, it could prove useful for distinguishing rockbursts from other simpler seismic source mechanisms.

4.5 Time Domain Amplitude Characteristics for Central European Events

Time-domain amplitude measurements have also been made for the central European events described in Section III. As with the South African events, the central European rockbursts normally produce strong seismic phases at regional stations. However, as noted above, the majority of the events are small so that signals beyond the regional distance range are usually not detected. Therefore, for our initial analyses of these data, we have concentrated on measurements at station GRFO, a high-quality regional station which has been operational over an extended period of time. Similar to the procedures applied for South African events, maximum L_g and regional P signal amplitudes were measured in the appropriate group velocity windows. For L_g we again took the start of the window to be at about 3.6 km/sec and the regional P window starting at about 6.5 km/sec.

The L_g and P_{max} measurements at GRFO were made for 26 events in the vicinity of Lubin, Upper Silesia, and one event with a location northeast of Lubin. Figure 30 shows these observations. For all these presumed rockbursts, the L_g signal amplitudes are larger than the corresponding maximum regional P signal amplitudes. The average L_g/P_{max} ratio is between 2.5 and 3. The largest L_g/P_{max} amplitude ratios tend to be for events in the Upper Silesia mining area primarily due to the weak P phases at GRFO from these sources. This may be related to the somewhat larger epicentral distance range for this source area compared to events around Lubin. It should be noted, however, that the Lubin measurements themselves show considerable variation with L_g/P_{max} ratios near 1.0 to more than 6.0. The latter also may be affected to some extent by small variations in the propagation distance for events in different source

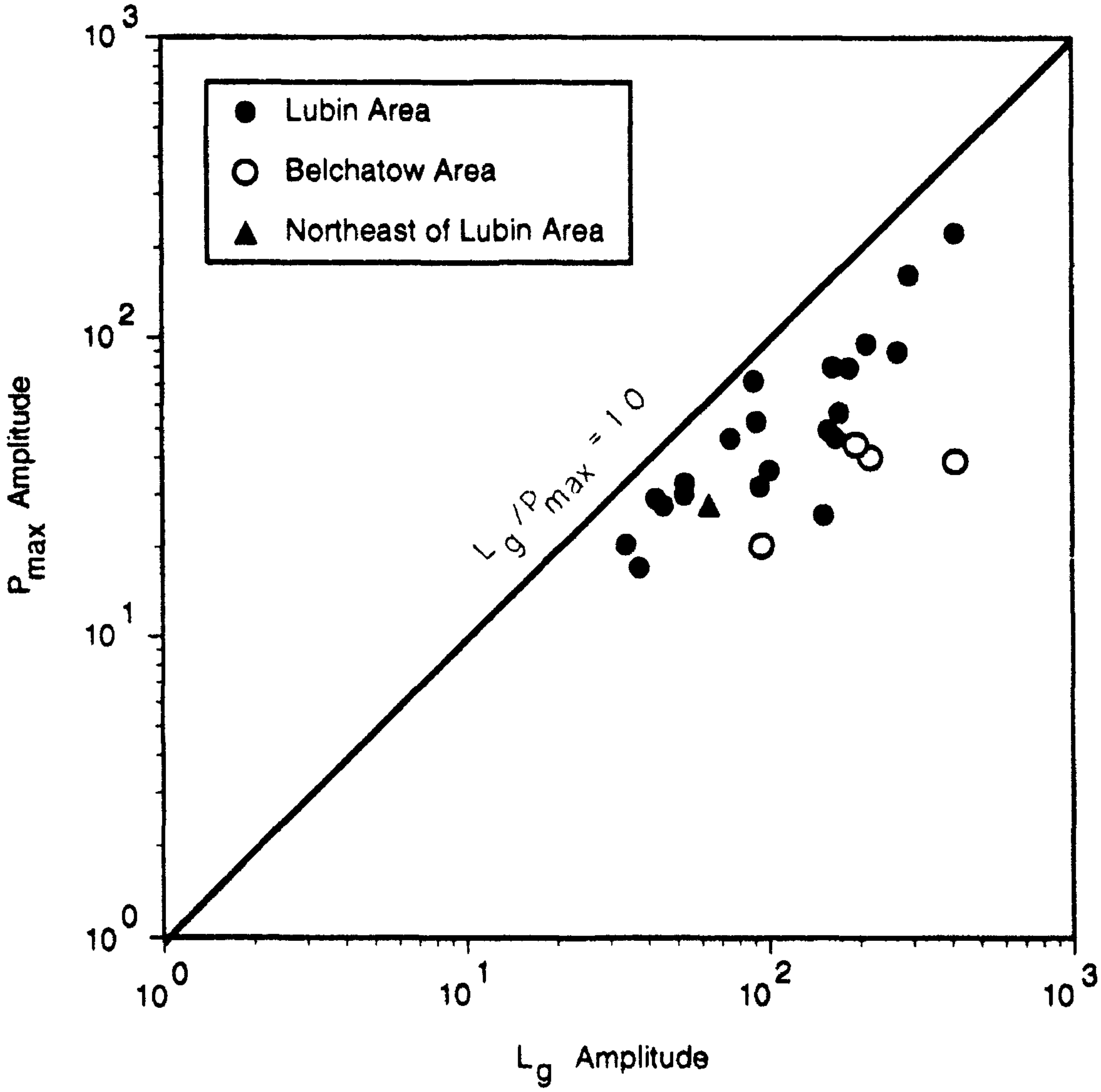

Figure 30. Comparison of maximum amplitudes in L_g and regional P windows at station GRFO for mine tremors in the Lubin and Upper Silesia (Belchatow) source areas.

areas and possibly by changes in source area site response. However, it seems likely that some of the variability is due to differences in mechanism, particularly for events that are close to one another geographically.

To date we have not identified many cases where Central European rockbursts have occurred in close proximity to natural earthquakes and mine blasts. This may be influenced to some extent by the lack of capability or need to distinguish one type of small seismic event from another. A recent study by Wuster (1992) is of some interest in this regard. The study involved 39 natural earthquakes and 22 surface blasts which occurred in the Vogtland area (at about 50°N and 12.5°E) as recorded at the GERESS regional array ($R \equiv 180$ km). The blasts had magnitudes near 2.0 M_L and the earthquakes had magnitudes between 0.7 and 3.0 M_L. We used the amplitude measurements reported by Wuster to prepare a P_{max} versus L_g plot similar to those described above. Figure 31 shows these reconstituted measurements for the Vogtland events. The L_g/P_{max} ratios in most cases are greater than 1.0 for both the mine blasts and the earthquakes. The blast ratios tend to be clustered at a value just above 1.0 while the earthquake ratios average between 2.0 and 3.0. The latter values are in about the same range and have similar scatter to the rockburst measurements shown above as recorded at GRFO. It should be noted that, even though the L_g/P_{max} ratios tend to be somewhat smaller for the small surface blasts on average, the scatter in the L_g/P_{max} ratios for the three event types tends to overlap. It may be possible to refine or improve these comparisons by restricting measurements to a common frequency band or by adjusting for instrument response. We are continuing to seek and acquire additional data which will permit more direct comparisons of the time-domain amplitude characteristics of rockbursts in Central Europe with other nearby event types.

4.6 Spectral Characteristics for Central European Events

We have also conducted spectral analyses of the seismic signals recorded at GRFO for a sample of rockbursts from the Lubin and Upper Silesia regions. Figure 32 shows the Fourier spectra for a representative event from each area. The Lubin event (10/02/80) had a magnitude of 3.9 M_L, and the Upper Silesia event (06/04/82) had a magnitude of 4.6 M_L. The spectra for the regional P windows are shown at the top and for the L_g windows at the bottom. We computed a spectrum for a pre-P noise segment from each event and used it to determine the signal-to-noise ratio as a function of

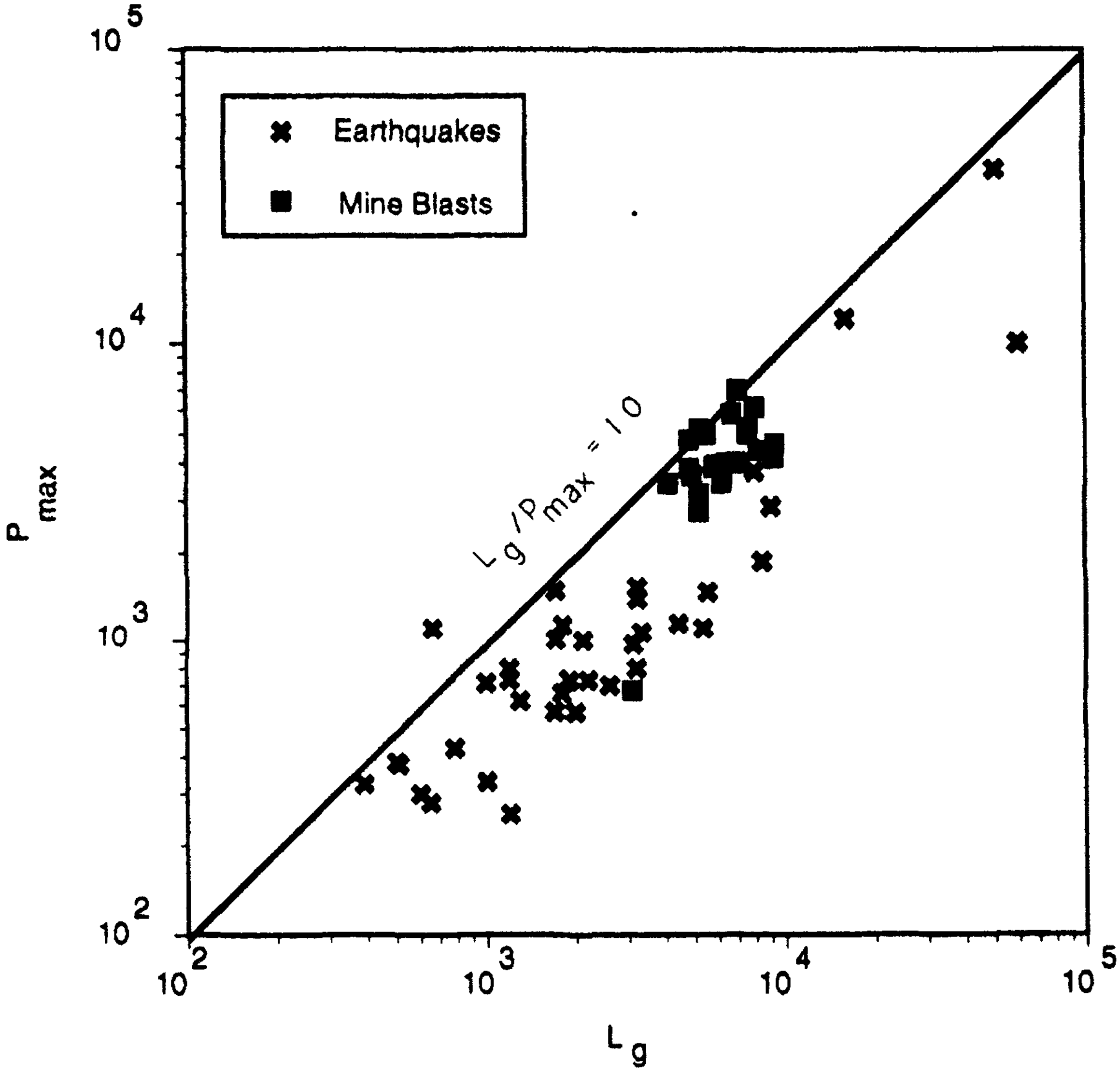

Figure 31. Comparison of maximum amplitudes in L_g and regional P windows at GERESS for earthquakes and mine blasts in the Vogtland source area (adapted from Wüster, 1992).

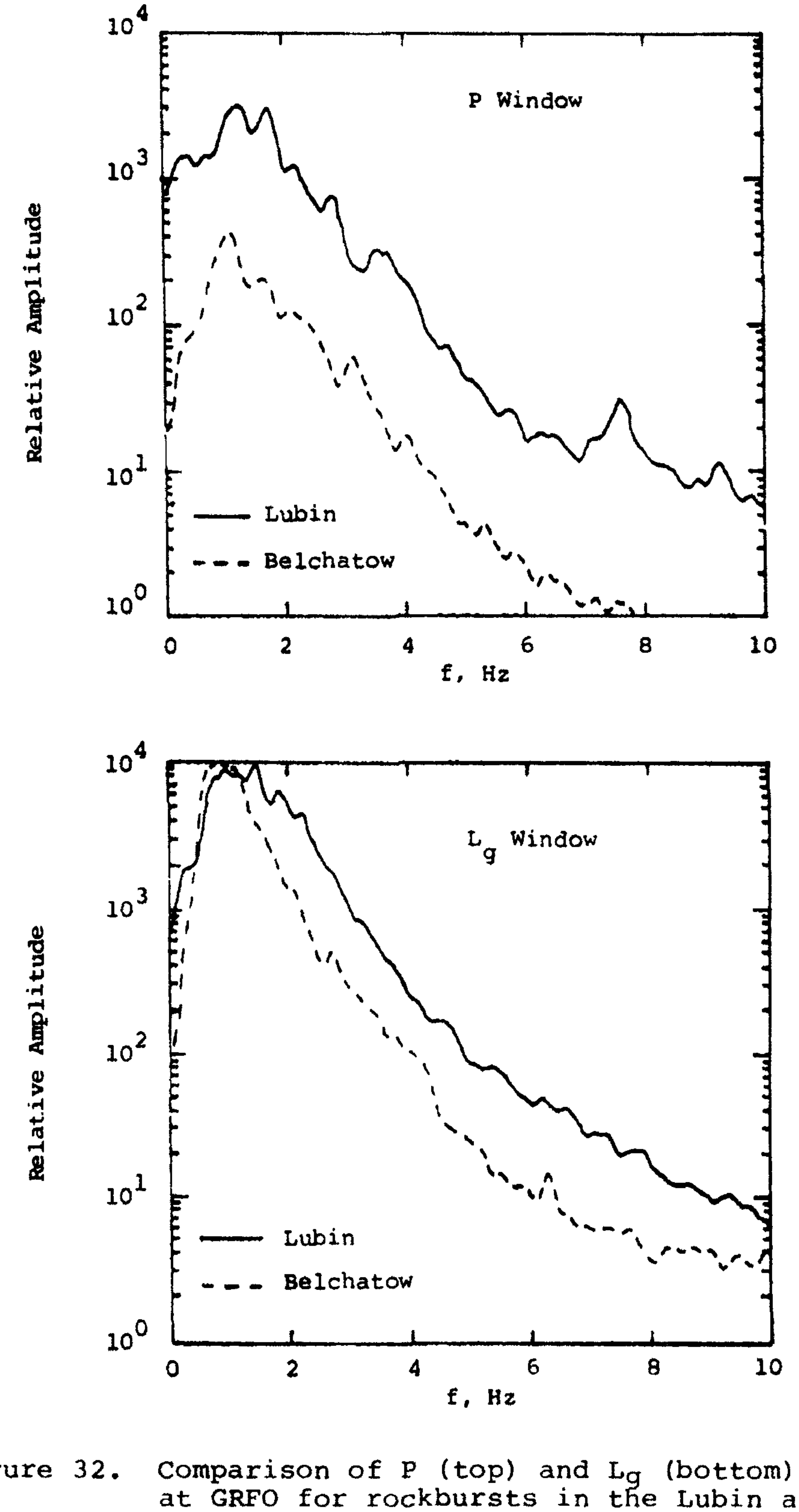

Figure 32. Comparison of P (top) and L_g (bottom) spectra at GRFO for rockbursts in the Lubin and Upper Silesia (Belchatow) source areas.

frequency. These S/N ratios had their maximum values for both phase types in the interval from 1 to 2 Hz where the S/N levels exceeded ten. The S/N levels were greater than 1.0 over the entire frequency band from 1 to 10 Hz for the relatively large events shown here. Smaller events, particularly those from the Upper Silesia area, have a more limited band of useful signals. In particular, smaller events from the Upper Silesia mining area produced P-wave signals above the noise only in a band from about 0.5 to 3 Hz, although L_g signals from the same events usually maintained a high S/N level over a much broader band.

The regional P-wave spectra for the Lubin and Upper Silesia events are similar in shape, as can be seen from the example shown in Figure 32 (top). Both spectra peak at a frequency slightly above 1.0 Hz. The spectrum for the Lubin event has a prominent secondary peak just below 2 Hz which, if present at all, has been severely attenuated for the more-distant Upper Silesia event. The main difference in the P-wave spectrum between the Lubin and Upper Silesia rockbursts is the generally lower level across the frequency band for the latter case. The difference is approximately a factor of 8-10 and shows no obvious change with frequency. It is unknown at this time whether this difference can be associated with source excitation or transmission effects. If the latter, the lack of frequency dependence is suggestive of P blockage rather than gradual attenuation related to Q. The L_g spectra in Figure 32 (bottom) both peak at frequencies below 2 Hz. The two L_g spectra also have maxima at about the same level, which is not too surprising considering that the Upper Silesia event had a larger magnitude but was also farther from the station. The Lubin rockburst L_g spectrum is enhanced at high frequencies relative to that of the Upper Silesia rockburst. This could correspond to an attenuation effect, but additional study is needed to determine whether or not some source difference might not also contribute to the observation.

Figure 33 provides more detailed comparisons of the P phases for two nearby rockbursts from the Lubin mining area recorded at GRFO. Since the two events are located in the same area, differences in the observed signals are more likely related to source variations between these events. The two events (04/10/81 and 01/16/82) had essentially the same magnitude, 4.8 m_b. Even in the time domain, several differences are rather obvious in the P_n and P_g signals shown at the top of the figure. The initial motions of the P_n phase appear to be opposite for the two events, although this is a little difficult to determine with certainty given their emergent character. A more certain observation is the increase in high frequencies for the 01/16/82 rockburst

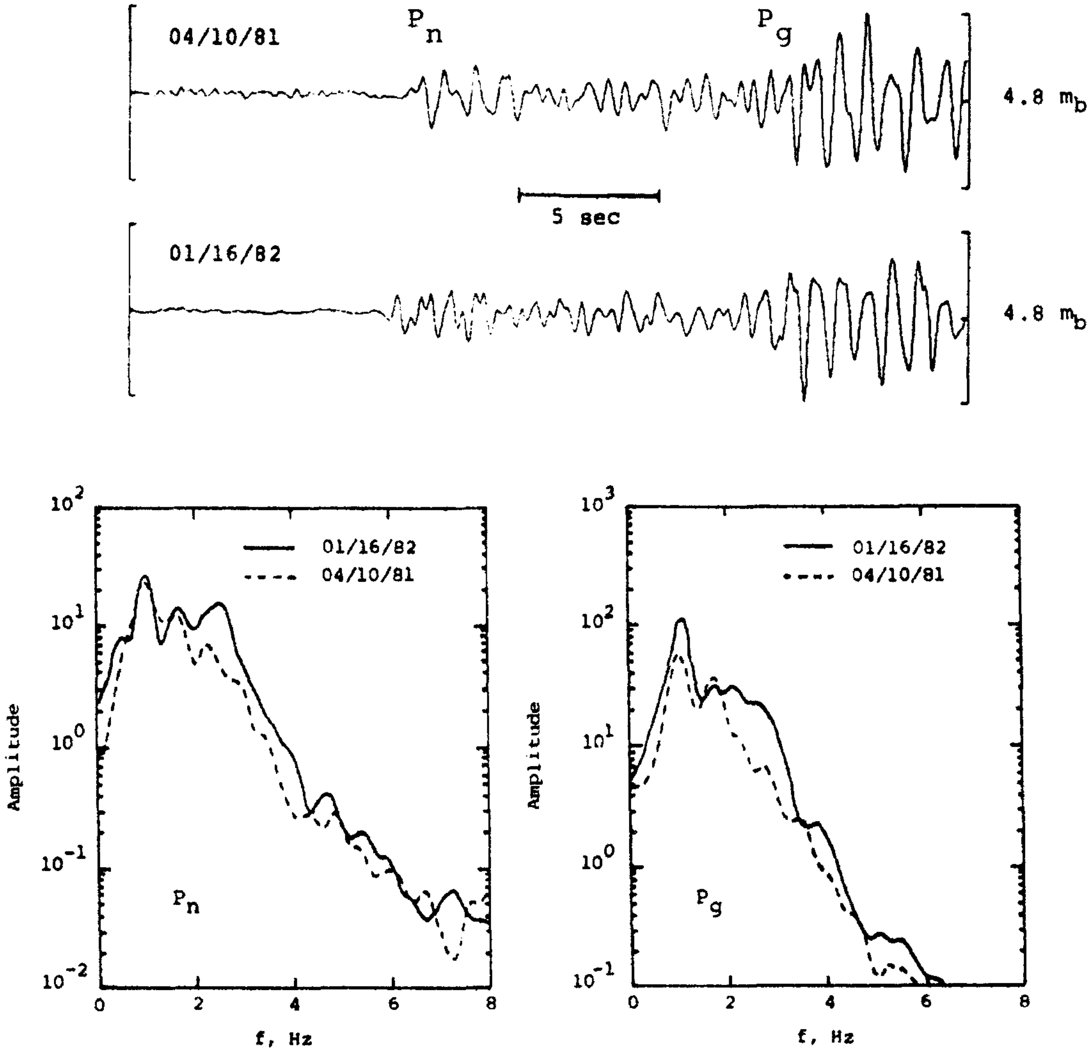

Figure 33. Comparison of regional P phases and their Fourier spectra from adjacent rockbursts in the Lubin area recorded at GRFO.

relative to the other event. We computed Fourier spectra for the P_n and P_g phases for these two events, and these are plotted at the bottom of Figure 33. For both events the P_n and P_g spectra peak at a frequency near 1 Hz. In fact, the spectra for both events match very closely up to 2 Hz, particularly for the P_n phase. However, above 2 Hz the spectra tend to be separated. Over the band from 2 to 4 Hz, the P_n spectrum is roughly twice as great for the 01/16/82 rockburst as for the 04/10/81 rockburst. In the same interval the P_g spectrum is about a factor of three larger for the 01/16/82 event. This observation, along with similar results from the South African events, would suggest that we can expect to see differences in regional signal spectra between rockbursts within a mining area which appear to be indicative of mechanism variation. Similar observations from additional events should help corroborate and define the range of variability which can be expected.

We are continuing to analyze regional signal spectral behavior for rockburst events in the Lubin and Upper Silesia mining areas recorded at GRFO and other European stations. We are investigating the variability as well as consistencies in the spectra between events in specific areas similar to studies described above for South African rockbursts. It is anticipated that these spectral analyses will lead to an improved understanding of the influences of source and propagation effects on the observed regional signals from rockbursts and other types of seismic events occurring in Central Europe; and this knowledge will be useful for understanding rockburst mechanisms in other parts of the world.

4.7 Spectral Ratios for Central European Events

We have computed L_g/P spectral ratios for a sample of Central European rockbursts recorded at station GRFO. Figure 34 shows the ratios for four such events. Two events (10/02/80 and 12/11/81) were in the Lubin mining area and had the same magnitudes, 3.9 M_L; the other two events (09/30/80 and 06/04/82) were in the Upper Silesia area and the magnitudes were "undetermined" and 4.6 M_L, respectively.

The L_g/P ratios for the Lubin rockbursts at the top of Figure 34 are seen to be somewhat oscillatory but remain generally above 1.0 over the entire frequency band from 0 to 10 Hz. The only exception appears to be a narrow band from about 2 to 4 Hz where the ratio falls to values near or just below 1.0 for the 12/11/81 event. Over the remainder of the band, the L_g/P spectral ratios match fairly closely for the two events.

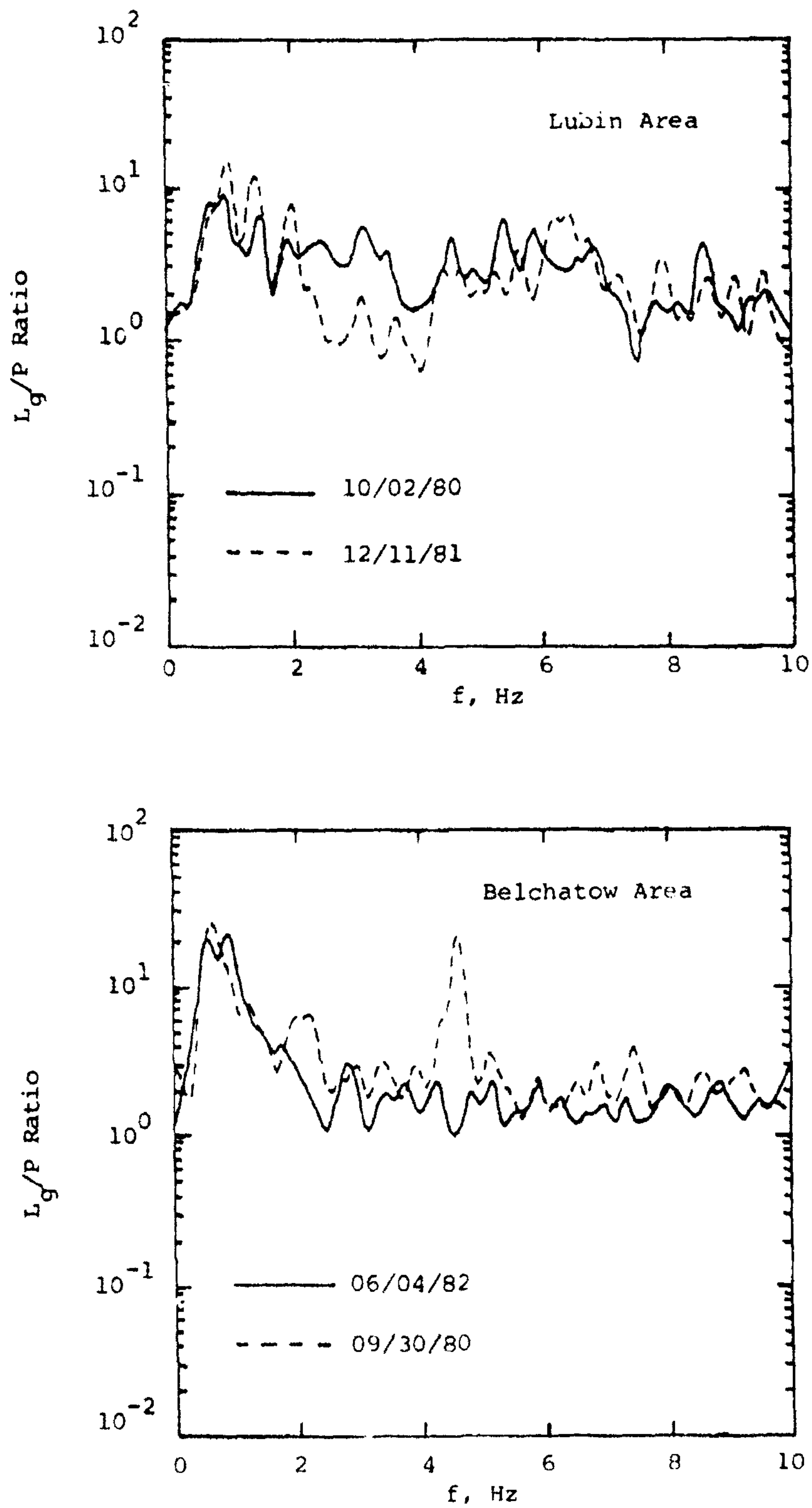

Figure 34. L_g/P spectral ratios at GRFO for mine tremors in the Lubin and Upper Silesia (Belchatow) source areas.

The maximum ratios occur in a band from about 1 to 2 Hz where the values approach ten. The ratios show a general decline over the range from 1 to 4 Hz. However, as was noted above for the South African rockbursts, the ratios contain some rather sudden fluctuations with frequency which may complicate interpretation of relatively narrow band observations.

The L_g/P spectral ratios for the rockbursts from the Upper Silesia mining area at the bottom of Figure 34 are quite similar between the two events. The ratios are again consistently above 1.0 over the entire frequency band. For both events the maximum value is rather sharply defined at a frequency just below 1 Hz. The L_g/P ratio at this maximum approaches a value of 20. Above 1 Hz the ratio declines out to 3 Hz to a level between one and two about which the ratio oscillates over the remainder of the frequency band. Because of possible noise contamination in the P signals at the higher frequencies for these Upper Silesia events, we are uncertain whether the L_g/P ratio plateau for these events is real. We plan to resolve this issue with additional analyses of the S/N levels for a broader sample of events from this source area.

The preliminary indications from these studies are that the L_g/P spectral ratios for Central European rockbursts tend to remain above a value of 1.0 over a broad band of frequencies. The studies by Bennett et al. (1992) for regional signals from earthquakes and underground nuclear explosions in Eurasia found that earthquakes had L_g/P spectral ratios above 1.0 over a broad band, but underground nuclear explosions had ratios which were high at low frequencies but rapidly dropped off below 1.0 at higher frequencies. Thus, with regard to this behavior, Central European rockburst tend to be similar in character to Eurasian earthquakes and different from Asian underground nuclear explosion tests. As the data become available, we plan to make additional comparisons of this type for more Central European events including small commercial blasts, larger rockbursts and earthquakes, and events in other parts of the region.

V. Rockburst Source Mechanisms

5.1 Characteristics of Different Types of Induced Events as Seismic Sources

The mining-induced seismic events described in Section II above include several different kinds of mechanisms. Many involve fault slip; others are caused by pillar collapse. Still others (mine bumps) are related to sudden onset of quasi-viscous flow of coal or other soft rock under the high pressures at depth and do not necessarily damage the mine opening. If rock is violently ejected into the mine opening, the tremor is identified as a rockburst. In some cases gas and associated coal or salt may be injected into the mine producing what is termed an outburst. Hasegawa et al. (1989) identified six distinct models for induced seismic events associated with mining: (1) cavity collapse, (2) pillar burst, (3) tensile failure of cap rock, (4) normal faulting above the advancing stope face, (5) thrust faulting on fractures above or below the excavation, and (6) shallow, near-horizontal thrusting between layers above the mine roof.

It seems clear that these various models should differ to some degree with regards to energy release and mechanism of seismic wave generation. Hasegawa et al. suggest that the cavity collapse mechanism can be represented as a simple downward vertical force. In contrast, the pillar burst and tensile failure could be represented as vertical and horizontal dipoles, respectively. They predict far-field P-wave and S-wave radiation patterns from these sources which are then different from the quadrantal patterns associated with the double-couple faulting models. Furthermore, the energy release associated with an individual rockfall or pillar burst would be expected to be quite small. On the other hand, for shear-failure in many mining areas tectonic stress appears to contribute to the mechanism, producing in some cases quite large energy release.

Analyses of observations from large mine-induced seismic events support the conclusion that such events are primarily associated with shear failure on faults or planes of weakness in the vicinity of the excavation (cf. McGarr, 1971; Spottiswoode and McGarr, 1975; McGarr et al., 1979). Bath (1984) found that rockbursts in Sweden represented sudden ruptures (not slow collapse) and apparently were caused by a shear-failure mechanism similar to that of earthquakes. Studies by Gibowicz (1984) of mine-related events in Poland and Gibowicz et al. (1991) of induced events in Canada also suggest the prevalence of a double-couple type mechanism. Sileny (1989) studied induced events in Czechoslovakia for evidence of mechanism complexity and found that even small events produced a predominantly shear mechanism consistent with the regional tectonic pattern. However, Sileny did find evidence of an implosive component combined with the shear slip. The implosive component was always small, amounting at most to 17% of the shear. Wong et al. (1989) found three types of seismic mechanisms associated with coal mining in the Wasatch Plateau of Utah. There the smallest, high-frequency events were apparently associated with gradual collapsing of the mine roof; and other double-couple events were related to mine-induced tectonic release. However, Wong et al. also found that some sub-mine induced events were characterized by a non-double-couple implosional focal mechanism.

In general, then, the majority of evidence appears to indicate that most large mine tremors have seismic mechanisms dominated by a double-couple associated with shear failure in the vicinity of the excavation. These events are usually closely associated with the prevalent tectonic stress conditions in the region surrounding the mine, so that the seismic mechanisms in the mine-induced events represent the response of fractures or zones of weakness adjacent to the excavation which are favorably oriented with respect to the ambient stress field. Induced events in some areas may have more complex mechanisms. These include events with an implosional component combined with the shear slip and small collapse events, represented as a simple vertical force. Evidence cited above (cf. Section II) suggests that the time of occurrence of rockbursts depends to some degree on mining practice, but the seismic mechanisms themselves appear to be influenced by mining practice for only the relatively weak events.

Young et al. (1989) describe rockbursts as seismic events triggered when stresses are redistributed on a tightly confined fault at depth. This stress redistribution, caused by the mine excavation, induces a frictional instability on the fault causing a shear failure to spread on the fault plane radiating seismic waves. Burridge and Knopoff (1964) showed that such a mechanism was equivalent to a double-couple source and produces the typical quadrantal radiation pattern. For such a model spectral analyses of the radiated body waves provides information about the rupture process. Typically the displacement spectrum consists of a flat low-frequency trend, a descending intermediate trend with slope proportional to between ω^{-2} and ω^{-3} and an upper frequency limit controlled by either attenuation or source properties (cf.

Madariaga, 1979). McGarr et al. (1990) compared various spectral measures of the sources for blasts and mine tremors observed in South African mines with those predicted from source models of various authors including Sharpe (1942), Archambeau (1968) and Brune (1970). They found that the spectral decay rate at high frequencies for body waves could not always be explained by a simple double-couple rupture model but could be adequately represented as a multiple rupture. Battis (1992) also finds some evidence for anomalous decay rates in body-wave spectra observed at regional distances from South African rockbursts, but his results also indicate a sensitivity in the observed spectral behavior to regional attenuation.

Kuhnt et al. (1989) distinguish between two different types of rockbursts: (1) a tectonic or dynamic type related to induced fault movement in the ambient tectonic stress field, and (2) a static type which is directly connected to the mining activities. For the second type event they have considered representations in terms of both barrier and asperity models. For the former, the surroundings of the pillars in the mine act as barriers to the crack propagating out from the stope area. In the asperity model, the pillars represent asperities which concentrate the stress and ultimately fail under the mining-induced stresses. In either model, since multiple pillars may be affected by a single rockburst, the distribution of barriers or asperities on the focal plane can be very complicated. Their calculations suggest the possibility of additional complexity in the rockburst source and variations in the sources between events which could be influenced by mining practice. It remains to be determined to what extent these kinds of source complexity contribute to the radiated seismic signals. As noted above, experience to date suggests that these kinds of complexity may have greater significance for relatively small events. However, it is conceivable that there may be some mining situations, outside the range of normal experience, where large events may have added complexity.

As this research program progresses, we will attempt to apply mathematical modelling techniques to analyze the effects of variations in mining practice and the mine environment on seismic signals. We will formulate a model representative of the different types of rockbursts described above. We will then use the model to evaluate differences between mines where rockbursts have been observed and to assess the potential variability between events in individual mines.

5.2 Seismic Characteristics of Rockbursts Useful for Potential Discrimination

Several characteristics of rockburst sources appear to offer some potential value in a seismic discrimination context. In particular, the fact that the majority of large rockbursts appear to have source mechanisms represented by a simple shear failure suggests that these events will produce earthquake-like seismic signals and should be distinguishable from explosions based on procedures similar to those used to discriminate earthquakes from explosions. Thus, we would expect the rockburst sources to produce non-uniform radiation patterns for P-wave signals like those for earthquakes. In Section IV above, we showed evidence that the initial P waves observed at a single regional station were not always compressional, as would be expected for an explosion. There also appeared to be some evidence of the effects of radiation pattern observable in P-coda phases at the regional station. However, it seems clear from Figure 20 above that observations from one or even a few stations will not always be reliable in identifying unusual mechanisms. First motions are frequently emergent and stations may need to be fortuitously located relative to the source. A regional network of stations appears to offer the best opportunity for identifying these kinds of differences, except for the very largest events where teleseismic stations could also play a role. The station requirements for such a comprehensive monitoring effort would seem to be extremely optimistic.

A second regional discriminant which should be useful for identifying rockburst events is the relative excitation of shear waves by the source. Most large rockbursts, like earthquakes, generate shear waves directly at the source unlike simple explosions which require some kind of secondary energy conversion for shear-wave generation. In Section IV above we showed evidence that L_g/P ratios for rockbursts in several different source regions were on average comparable to those seen for earthquakes throughout the world. This suggests the possibility that this kind of regional measurement or others dependent on shear-wave excitation (e.g. L_g spectral ratio or L_g/P spectral ratio) will enable the distinction of rockbursts from explosions. It should be noted, however, that refinements of these techniques will certainly be required for individual source regions to reduce the measurement scatter from explosions, rockbursts and earthquakes which might otherwise lead to oversights or false alarms.

We are still investigating some of the more traditional discriminants as they apply to rockburst events. Discriminants based on differences in depth between explosions and earthquakes certainly would not be expected to be effective for distinguishing explosions from rockbursts. As described in Section II above, rockbursts normally occur at depths from a few hundred to, at most, a few thousand meters. This is exactly the range of depths where underground nuclear explosion tests occur. The M_S versus m_b discriminant as applied to rockbursts needs further study. In Section III above we showed that it should be possible to observe the long-period Rayleigh wave signals from larger rockbursts at far-regional stations. With some additional effort a regional M_S scale could be established for quantifying the relative Rayleigh-wave excitation versus other signal types from rockbursts and other events within a particular region to test the consistency of such measurements and evaluate their potential usefulness as a discriminant.

Another discriminant which has received attention in recent years is spectral scalloping arising from multiplicity or extended duration in complex sources. The situation receiving the greatest attention has been ripple-firing used in commercial blasting operations. Although the situation with rockbursts is somewhat different, the discussion above of complexity in rockbursts arising from mining practice suggests the possibility of multiple sources separated in time and space (e.g. the failure of multiple pillars). Such a model could lead to spectral scalloping of the regional phases similar to that observed from some quarry blasts. In addition, the rather rapid spectral decay rates for body waves, which appear to be associated with source complexity for some South African events, suggest that other spectral discrepancies may be observable for rockburst events. If such complexity is significant for larger events, evidence might also be detectable as differences in teleseismic P-wave spectra. We expect to investigate the effects of such sources of signal complexity using mathematical modeling, as noted above.

In general, then, many rockbursts have mechanisms similar to earthquakes. For these events discrimination procedures which are effective for earthquakes also should work in most cases for rockbursts. Because most rockbursts are small, regional discrimination techniques may have added significance in their identification. It is important to note in this regard that, although a number of promising techniques have been put forth, no reliable regional method for discriminating small earthquakes and explosions has yet been firmly established. Complexity in the rockburst source may also give rise to spectral differences in regional and teleseismic signals which distinguish those events from simpler, shorter-duration source types such as underground nuclear explosions.

5.3 Evasion Scenarios Using Rockbursts

As described in Section II above, rockbursts or mine tremors occur in mining areas all over the world. In some areas the rate of rockburst occurrence is quite high, and in a few areas the induced events are quite large. This presents a problem for discrimination of possible nuclear explosion tests down to low thresholds in mining areas because of the large number of events which need to be identified. The problem is made worse by the possibility of using a rockburst to deliberately conceal a small underground nuclear test. Assuming the rockburst is large and located relatively close to the nuclear test, signals from a small or decoupled explosion may pass undetected. The problem in this case is somewhat different from the hide-in-earthquake scenario which has been previously considered in that the source location of the explosion and the rockburst may be practically indistinguishable. Furthermore, it may be feasible to control or know in advance the time and size of the rockburst, a luxury not currently afforded by earthquake prediction.

High-frequency seismic monitoring networks have been operated for many years in the vicinity of mines where tremors occur in an effort to identify the conditions leading up to damaging events. In addition, mining engineers have developed rather sophisticated finite element techniques for analyzing stress conditions in the rock surrounding mining excavations in areas where rockbursts are a problem (cf. Russell et al., 1983; Wong, 1984). As a result of these and other corroborative monitoring programs, capability is now available to predict rockburst occurrence and level with some accuracy.

An interesting case in point is the experience in the Mufulira copper mining district of Zambia described by Russell et al. (1984). Using a three-dimensional finite element code in combination with two-dimensional analyses for specific areas, mining engineers were able to make precise predictions of the locations and stress levels with the mine where rockbursts could be expected, where spalling would occur, and where damage would be limited to minor flaking. This program indicates that it is possible to use computer models to fairly accurately predict the regions in a mine which are on the verge of failure and, by removal or addition of backfilling material and pillars to either reduce the stress below the critical level, or to increase it to the point of inducing a rockburst in some particular magnitude range.

Therefore, one evasion scenario which should be considered in further analyses is the possibility of testing a small or decoupled nuclear explosion in a mining area. The level of effort required of the potential evader ranges from attempting to include the explosion in the normal background noise of mine tremors to an effort to simultaneously trigger a large rockburst to mask the signals from the nuclear test. An important issue with regard to the latter is to what degree can large rockbursts be controlled. We are continuing to investigate this problem.

VI. Summary and Conclusions

6.1 Report Summary

The research described in this report deals with a type of seismic event (viz rockbursts) which prior to this has not received much attention with regards to discrimination. The frequent occurrence of rockbursts in mining areas all over the world could present problems for routine discrimination at low thresholds unless procedures are identified to facilitate their identification. Furthermore, the possibility of controlling rockbursts in some mining areas may provide an opportunity to conceal a small or decoupled nuclear explosion test.

This research program is aimed at characterizing the seismic behavior of rockbursts and other stress-release events associated with mining for use in their discrimination. Initial efforts in this program have focused on data collection, some preliminary analyses, and review of literature on rockburst occurrence throughout the world. By considering the phenomena and seismic observations associated with rockbursts in a variety of mining environments, it should be possible to discern common factors which will aid in identification. For this study, then, we have reviewed reports on rockbursts from many different regions around the world. We have also collected seismic data from rockbursts, and other events for use in comparison, in many different source regions. In this report we have focused consideration on data from two areas (viz South Africa and Central Europe) where rockbursts have been frequent and, in many cases, have been quite large.

In addition to assessing the mining conditions associated with the occurrence of rockbursts in these areas, we have sought to put together a seismic database representative of the signals recorded at regional, far-regional and teleseismic stations for events from these areas. These seismic data for South African and Central European events have been collected primarily from high-quality digital stations of the GDSN and, more recently, IRIS network, supplemented by several events from the GSETT-2 experiment. We have performed a variety of amplitude and spectral measurements on the recorded signals and have attempted to assess common features as well as variability between events. Finally, we have developed some preliminary hypotheses regarding identification procedures which may be useful for discriminating rockbursts and other mine tremors.

6.2 Principal Conclusions

Based on the analyses which have been conducted to date, we conclude that rockbursts or other mine tremors could represent a significant problem for seismic discrimination monitoring at low-threshold levels throughout the world. We base this on reports indicating that rockbursts are frequent, occur in most mining areas, may show mechanism complexity, and may be controlled to some degree by mining practice. Most of the data we have analyzed from South Africa and Central Europe indicates that rockbursts have seismic signal characteristics similar to earthquakes. This knowledge should be useful in designing discrimination methods for routine identification of such events. However, the significance to seismic identification of more complex mechanisms and ability to control rockburst occurrence in some mines requires further investigation.

Rockbursts or other types of stress-release events are prevalent in most types of underground mining and may even occur with surface excavations in areas of high tectonic stress. Although the magnitudes of most events associated with mining are small, in some mining regions the magnitudes may occasionally, or even regularly, exceed 5 M_L. The phenomena and environment associated with rockburst occurrence in different mining areas appears to involve some common elements; but there may also be elements in the observations unique to specific mines. Factors affecting rockburst occurrence related to the mining environment include depth of the mine, strength of the rock adjacent to the excavation, presence of preexisting fractures or zones of weakness in the rock, and tectonic stress conditions in the region of the mine. In addition, mining practices, such as rate of material removal, areal extent of the excavation, and mine geometry, may influence the size, frequency, and mechanism of induced seismic events in some mining situations. Because of the effects of these different factors, the seismic signals from rockbursts may be expected to vary between mining districts and possibly even within a particular mine.

The database assembled to analyze these factors includes 69 events from southern Africa recorded primarily at GDSN stations and 44 events from central Europe recorded at GDSN and GSETT-2 stations. For the South African events, excellent regional recordings are available from the DWWSSN station SLR for many of the smaller rockbursts and presumed regional earthquakes. In addition, many larger South African rockbursts produce good P-wave signals at teleseismic stations. For the Central European rockbursts the only GDSN station of practical value for monitoring most of the smaller events is GRFO. Good waveform data are also available for some small to intermediate magnitude events in Central Europe, including a few mine tremors, recorded during the GSETT-2 experiment. A few larger events are expected to be better recorded at more distant stations, but we are still collecting those data.

L_g/P amplitude measurements obtained from time-domain measurements at regional stations for South African and Central European rockbursts are observed to be generally greater than 1.0. These ratios are similar to those measured in this study for nearby regional earthquakes. These L_g/P ratios are consistent with values obtained for regional earthquakes in many other parts of the world, as well, and may offer a potential discriminant versus underground nuclear explosions, for which similar ratios are generally smaller. L_g/P spectral ratios for rockbursts in South Africa and Central Europe have values well above 1.0 over a broad band of frequencies. The spectral behavior of the ratio is again seen to be similar between the rockbursts and regional earthquakes. Similar L_g/P spectral ratios for underground nuclear explosions, observed in previous studies, generally fall below 1.0 at frequencies above about 2 Hz. Preliminary results of the computations of P-wave spectra from teleseismic stations for some large South African rockbursts indicated surprisingly large S/N levels with values, in some cases, above 1.0 up to 8 Hz. P-wave spectral ratios between events at specific teleseismic stations showed some consistency; but they also had rather large fluctuations with frequency, which could be indicative of variations in source complexity between rockbursts.

Much of the literature published on source mechanisms for rockbursts in several mining areas suggests that large events can be represented by a shear-slip model similar to earthquakes. This rockburst mechanism represents slip on fractures or pre-existing zones of weakness adjacent to the excavation which are favorably oriented with respect to the ambient stress field. For rockbursts of this type, discriminant measures which work for earthquakes should be effective. However, there is also evidence that at least some small mine-induced events have had more complex source mechanisms, which depend more on details of the mining practice. It remains to be determined to what extent such complexity can be controlled by mining practice for larger events and how it will affect seismic signals. If the occurrence of large rockbursts can be controlled, as some studies indicate, they could present a potential problem for identification of a small nuclear test masked by a large rockburst which has been deliberately triggered in the same mining area.

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